BODY SWAY AND AIM POINT FLUCTUATION IN RIFLE AND PISTOL SHOOTERS

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ABSTRACT

This study examined the effects of quantisation of force plate data used to measure body sway and the relationship between this body sway, aim point fluctuation and performance in shooting. Quantisation error in and resolution of selected body sway parameters were calculated from force plate data sampled using 12-bit and 16-bit analog to digital conversion (ADC). It was concluded that 12-bit ADC does not offer adequate precision when assessing the body sway of shooters and that 16-bit ADC is required. The relationship between body sway, aim point fluctuation and performance was examined on both group and individual bases. Body sway was measured in six elite rifle and five elite pistol shooters while performing 20 shots in simulated competition conditions over 5s, 3s and 1s before shot using an AMTI LG6-4 force plate and 16-bit ADC. This was synchronised with a SCATT shooting training analysis system, which measured aim point fluctuation and performance. From 16 time-based body sway parameters quantified, principal components analysis identified four body sway factors, which related to the amplitude and speed of this sway in both the X and Y axis. Using four body sway parameters that represented these factors, correlation and multiple regression analysis indicated that body sway, aim point fluctuation and performance were related for some but not all shooters. Further, this association was specific to the individual shooter in terms of degree and direction of association, the axis of influence of body sway and aim point fluctuation and the time period. This highlighted the importance of individual based analysis in elite shooting. Further research with larger subject numbers, aim point fluctuation more thoroughly examined and including kinematic analysis may assist in better defining the relationship between body sway, aim point fluctuation and performance.

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TABLE OF Contents

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

Shooting is an Olympic sport, with over fifteen different categories. Standing Air Rifle and Pistol Shooting are among the most technical of these, with both disciplines requiring extreme precision for success. From a standing position, the shooter must aim at a target located 10 metres away which, in the case of rifle shooting, has a “ten ring”, or “bull’s eye”, 1mm wide. The bullet must touch this ring to score a ‘ten’, allowing for an angular movement of the gun of only 0.016° (Zatsiorski and Aktov, 1990). Not surprisingly then, the smallest of movements will significantly affect a shooter's score.

Although shooting has been scantly researched, studies have covered a number of psychological, physiological and biomechanical factors. The effects on performance of heart rate, respiration timing and respiration amplitude (eg. Tremayne *et al.*, 1993), brain wave patterning (eg. Konttinen and Lyytinen, 1993) and arousal levels (eg. Mason and Bond, 1989) have been examined. The limited amount of biomechanical research in shooting has focused on the influence of body sway and aim point fluctuation on performance (eg. Mason *et al.*, 1990; Niinimaa and McEvoy, 1983; Zatsiorski and Aktov, 1990).

The influence of body sway on shooting performance is a logical area of study, due to the very precise movements required in shooting and the potentially large gun movements that may be generated by body sway. Shooters have been found to produce smaller sway amplitudes than the general population (eg. Aalto *et al.*, 1990) with centre of pressure (COP) ranges of less than 1mm reported (eg. Viitasalo *et al.*, 1997). The small amount of sway produced by shooters requires extremely accurate measurement. Commonly, this measurement has been performed using a force plate and a 12-bit analogue to digital converter (ADC). The three areas of error that may exist in force plate data collection that will influence the measurement of body sway are equipment error, noise and quantisation error. Although quantisation error is considered a type of noise, it will be treated separately in this study. Equipment errors include plate distortion and transducer cross talk. Noise, generated from sources external and internal to the system, such as amplifier noise or 50Hz main power noise, can be sensed by the system and recorded as part of the signal. The third area, quantisation error, refers to the difference between the analogue signal and the binary coded digital representation of that signal (Baher, 1992). Based on data obtained from a force plate using a 12-bit ADC system, Wisleder and McLean (1991) report that quantisation error is the major source of error in COP calculations when dealing with sports in which exceptional stability is required. Early experiments for this study also indicated that 12-bit ADC was inadequate for the measurement of some body sway parameters, particularly first derivative data such as COP velocity. It is quantisation error that will be the focus of stage 1 of this study- by comparing 12-bit ADC and 16-bit ADC in terms of the resolution provided and the error potential for body sway measures during shooting due to quantisation.

There have been conflicting results from the small number of studies examining body sway in pistol shooting. Mason *et al.* (1990) identified body sway as the major contributing factor to shooting performance in pistol shooting at the elite level. However, Aalto *et al.* (1990) suggest that body sway is unimportant in pistol shooting, with other skill factors more influential to performance. This contention does not exist in rifle shooting. However, while rifle-shooting studies have shown that differences exist in body sway control between elite and non-elite rifle shooters (eg. Era *et al.*, 1996), and that body sway is associated with performance when shooters from a wide range of skill levels are examined (eg. Viitasalo *et al.*, 1997), no study has shown an association between body sway and performance at the elite level. Problems of insufficient measurement precision may have influenced these studies, with 12-bit ADC force plate measurement used to assess body sway. Another limitation of these studies was the within-group analysis method, with no within-individual analysis reported. With the small amount of variability that is likely to exist in elite shooting groups, this method of analysis may reduce the chance of finding significant associations between body sway and shooting performance. The examination of body sway, measured using a 16-bit ADC system, and its influence on shooting performance will be examined in stage 2 of this study, with this examination conducted on a group and individual basis.

Aim point refers to the location on the target that the gun aligns with, or put simply, where the gun is pointing. Aim point fluctuation refers to the movement of the aim point on the target. This is another logical research focus, as performance is dependent on the location of the aim point at the instant of shot. The relationship between aim point fluctuation and shooting performance has been explored and found to hold pertinent information for the competitor (eg. Zatsiorski and Aktov, 1990; Lu, 1989). However, while associations between aim point fluctuation and performance exist when shooters from a wide range of skill levels were examined (Viitasalo *et al.*, 1997) and elite level shooters have been shown to produce less aim point fluctuation than non-elite shooters (eg. Norvapalo *et al.*, 1997), no studies have shown an association between aim point fluctuation and performance at the elite level. The same difficulties of finding statistical significance in an elite group when assessed on a within group basis only exist for the relationship between aim point fluctuation and performance. Stage 2 of this study will also correlate aim point fluctuation and performance on a group and individual basis.

There are no reports examining the relationship between body sway and aim point fluctuation during standing rifle shooting or standing pistol shooting. In running target shooting, an association between body sway and aim point fluctuation has been found when shooters with a wide range of skills were tested, but not when the elite group was examined in isolation (Viitasalo *et al.*, 1997). The examination of the relationship between body sway and aim point fluctuation on a group and individual basis will form a part of stage 2 of this study.

In summary, this study will be presented in 2 stages. Stage 1 will examine the accuracy of 12-bit and 16-bit ADC data capture for measurement of body sway in shooting. Stage 2 will examine the relationship between body sway, aim point fluctuation and performance in elite pistol and rifle shooting with this examination conducted on a group and an individual basis.

CHAPTER 2 REVIEW OF LITERATURE

2.1 Errors in force plate data collection

A force plate is used to measure the forces that are exerted at the ground. Briefly, it consists of a top plate and a bottom plate connected in each corner by a transducer (figure 2.1). Each transducer measures the force produced by the top plate on the bottom plate in three orthogonal axes, denoted by Fx, Fy and Fz.

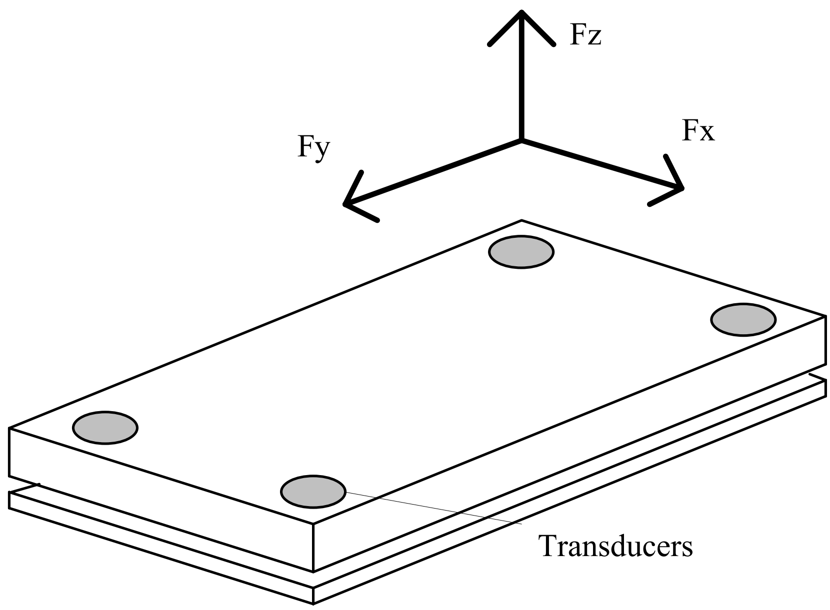


Figure 2.1: A typical force plate with four transducers top and bottom plate and three orthogonal measurement axes.

Errors in measurement using force plates can be generated from three sources: equipment, noise and quantisation error.

2.1.1 Equipment

Equipment set-up is considered carefully during laboratory construction. Force plate manufacturers provide installation guidelines for plate mountings and surrounds (eg. AMTI, 1982). Briefly, these involve locating mountings on a concrete block on the ground floor of a building. This block should be isolated from the surrounding building to reduce the effects of building vibration and building movement on the signal output. Precise levelling of force plates is necessary for accurate alignment of axes to obtain true forces and torques. The choice of overlay on the force plates must also be given consideration to minimise force attenuation whilst maintaining the safety and integrity of ‘competition like’ settings, as well as remain level with the surrounding floor.

Bartlett (1992), in guidelines for force plate measurement, report that valid force measurement requires force transducers which exhibit adequate sensitivity, low threshold, high linearity, low hysteresis, low cross-talk and adequate temperature tolerance. Cabling needs to be considered also to reduce the generation of electrical noise from inductance and to minimise the environmental noise, which may be sensed by the cables, through adequate insulation. Calibration of the system can reduce the potential errors that any of these factors may introduce.

The centre of pressure (COP) is the point of application of the ground reaction force vector on the force plate surface. COP measurement, particularly during the measurement of quiet stance, requires extreme accuracy of all these components and tests the force plate set-up to its limits. Force plate manufacturers report COP errors of up to 30mm (Kistler, 1997). While this is an upper limit for COP error, COP ranges during shooting have been reported as less than 4mm (eg. Mason *et al.*, 1990; Viitasalo *et al.,* 1997). Measurement of this magnitude of movement requires greater accuracy than the potential maximum error quoted above.

Bobbert and Schamhardt (1990) examined the COP accuracy produced by a Kistler force plate of dimensions 600mm in the X-axis and 900mm in the Y-axis. On the application of a point source of known force to 117 COP locations on the force plate, average COP displacement errors of 3.5mm in the X-axis and 6.3mm in the Y-axis were found to exist. The researchers eliminated likely sources of this error, such as cross talk between transducers and nonlinearity of individual transducers. Bobbert and Schamhardt concluded that distortion of the force plate itself caused this error. This plate distortion changed the angle of applied force on each transducer, which then generated a slightly different force value as a result. Further, the researchers found that the discrepancy between actual and measured COP position varied systematically at different plate locations. Based on these findings, a COP correction algorithm was developed, which reduced the average COP displacement error to from 3.5mm and 6.3mm to 1.3mm and 1.6mm in COPx and COPy respectively. Sommer *et al.* (1997) developed correction algorithms for a range of Kistler plates, which reduced mean COP errors from 14.1mm to 5.8mm for the same model force plate as used by Bobbert and Schamhardt. While slightly different methodologies were used, the difference in errors found in each study is unclear.

The algorithms presented by Bobbert and Schamhardt (1990) and Sommer *et al.* (1997) improve COP accuracy for point source applications of force. However, the method of assessment of COP may not apply directly to situations where more than one point of force application or application areas exists. In the case of quiet stance, there are two areas of application of force- under each foot. Distortion of the force plate will probably differ due to the different loading pattern compared with a similar mass concentrated on a single point. This will reduce the algorithm's effectiveness for reducing COP errors. The errors in COP measurement due to force platform distortion have been shown to be reduced when a known load is placed on a force plate at two areas, rather than at one point (Middleton *et al.*, 1999). Further, Bobbert and Schamhardt used an aluminium plate on top of the force plate that would tend to alter the distorting effect of the applied force to the force plate. To this author's knowledge, force plates built by other manufacturers have not been examined to improve COP measurement.

A number of factors will reduce the potential error due to plate distortion. First, as mentioned, Middleton *et al.* (1999) found smaller errors in COP measurement when a load was applied at two areas, rather than at a single point. During the shooting stance, a load is applied to the force plate at two areas (at each foot). As such, reduced error due to force plate distortion can be expected during this assessment, compared with the error reported by Bobbert and Schamhardt (1990). Second, shooters have been shown to move minimally. For example, COP ranges have been reported to be approximately 3mm for pistol shooters (Mason *et al.*, 1990) and 2mm for rifle shooters (Viitasalo *et al.*, 1996). While the plate may be distorted during body sway measurement, this distortion will remain relatively constant throughout the trial, particularly as the COP moves through only 2-3mm during measurement. As such, the error due to the distortion will also remain relatively constant throughout the trial. As most body sway measures used in posture assessment and in this study depend on a change in COP position, at least part of this error due to distortion of the plate will be eliminated in calculations due to the distortion remaining fairly constant. Third, most parameters used in posture assessment are relative measures such as averages, areas and ranges where the absolute measures of COP are not important, only the change in COP position. These measures will, in themselves, reduce the effect of systematic and random COP inaccuracies.

2.1.2 Noise

All measurement involving electrical signals will be a combination of true signal and noise (Baher, 1990). Noise can be generated from sources both internal and external to the measurement. External noise exists in the surrounding environment and may be generated by mains power and building vibration. This noise can be sensed by the force plate or cabling between the plate and the computer. The force plate transducers, the amplifiers and the ADC board in the computer can generate internal noise.

While most studies deal with the issue of noise in the form of smoothing of data, there does not seem to be a large deal of literature reporting specifically on the issue of noise in force plates, presumably due to its largely system specific nature. As such, there is a limit to the applicability of the findings of research outside of the specific system on which the research was conducted. Granat *et al.* (1990) report that when using digital techniques for sampling measurement error is generated by small amounts of noise and quantisation effects. To examine this error source and assess the effects of smoothing, a 100N weight was placed on a Kistler force plate and sampled using a 12-bit ADC system at 60Hz. Sample time was not reported. Prior to filtering, a speed of 1.7mm/s was found. Although not reported, it is assumed that this refers to COP movement. Filtering using a FIR (finite impulse response) low pass digital filter with a cut-off frequency of 7.5Hz reduced this speed to 0.05mm/s, which was considered suitable by the authors for most applications.

While smoothing can reduce error due to noise, as found by Granat *et al.* (1990) it cannot be completely eliminated. Noise of similar frequency to that of the true signal cannot be removed without removing true signal also. The selection of smoothing cut-off frequency is a compromise between the amount of signal and noise in the filtered data (Winter, 1990). As such, some amount of noise will always exist in a signal.

2.1.3 Quantisation

When a signal is measured as a voltage, it is quantified by passing through an analogue to digital converter (ADC). The finite number of points that can be used to measure a signal directly affects the level of precision that can be obtained. For example, a 12-bit ADC uses (2^{12}), or 4096 measurement steps, during conversion, usually across a ±10 Volt range. If the maximum measurement for a signal is ±2000N, then each step in measurement will equal approximately 1N. This means that any signal which lies at a fractional number will be rounded up or down and may fluctuate between the two values. The error generated by this process is a type of noise and is termed quantisation error and is the difference between the analogue signal and the binary coded digital representation of that signal (Baher, 1992).

Research specific to quantisation in force plate data collection is scarce. Wisleder and McLean (1991) examined the COP output of a series of different stationary weights on a Kistler force plate, reporting COP ranges of 3.1mm in the X-axis and 4.8mm in the Y-axis. The researchers concluded that quantisation error was the cause of the weights 'moving'. Further, this error was found to increase as the vertical force (Fz) decreased below 800N. Wisleder and McLean suggested that this error may become significant, particularly when the value of Fz is low and the movement being measured was small, as in the case of posture control and particularly in shooting analyses. While quantisation error would account for large incremental jumps in the measured signal, noise or limitations of the electronics in the system must also exist to cause the fluctuation of the values over more than two ADC units.

Aalto *et al.* (1988) presented a means of filtering force plate data to eliminate quantisation error. This involved applying a three point moving window across the complete dataset. In each window of three points, the median value was chosen to represent the data at the midpoint of the window. A moving point average was then applied to this adjusted data. A reduction of 65% in COP sway velocities was reported using this smoothing method. Unfortunately, the method was assessed only by comparing subject data obtained using this smoothing technique with data obtained by other authors, making it difficult to assess the quality of the process. No direct comparison with a known result, such as a weight placed on the force plate, was reported.

In summary, three sources of error exist in force plate data collection. Problems with equipment have been shown to affect COP measurement in Kistler plates. No studies have examined this problem in the AMTI force plates, which will be used in this study. Assessment of this type is beyond the scope of this study and remains a possible limitation of COP measurement. Noise will affect force plate measurement, but is largely system and environment specific. As such, this issue must be dealt with on a system specific basis. Noise in the COP signal is dealt with in the smoothing analysis (Appendix D). Quantisation is a problem that holds a general application, as hardware and software set the quantisation resolution available. The resolution that is offered by 12-bit ADC systems, used in previous shooting studies (eg. Mason *et al.*, 1990; Niinimaa and McEvoy, 1983), may not be accurate enough to provide discerning information when dealing with elite shooters. This area is examined in stage 1 of this study.

2.2 Body sway

2.2.1 Centre of pressure (COP)

COP, calculated from force platform data, has been used to assess body sway in most biomechanics shooting research reviewed by the author (eg. Mason *et al.,* 1990; Bozsik *et al.*, 1995; Viitasalo *et al.*, 1997). Inherent in this measure of body sway is the assumption that the larger COP movement indicates a less stable subject. In shooting competition settings, COP has been measured over different time periods prior to the shot (1s-7.5s). Table 2.1 summarises the COP parameters used in shooting studies.

Table 2.1 Summary of COP parameters used in shooting research

COP Parameter		Definition	Studies in which the parameter has been used
Displacement	Range	difference between maximum and minimum COP values	Mason *et al.*, 1990 Viitasalo *et al.* 1997
	Standard deviation	Deviation of COP location	Norvapalo *et al.*, 1997
	Length	total length, or distance, traced by the COP path	Niinimaa and McEvoy, 1983
	Area	percentage time spent within a given area	Bozsik *et al.*, 1995
Velocity/speed	Average		Wu *et al.*, 1997
	Maximum		Wu *et al.*, 1997
	Standard deviation		Norvapalo *et al.*, 1997

While COP is the most commonly used measure to assess body sway for shooters, it should be noted that COP movement is not a direct measure of postural sway. Body sway refers to the oscillation of the centre of gravity (CG) about a mean point, while COP is the point of application of the resultant force generated by the shooter. The two are related but not the same. Winter *et al.* (1993) reports that during upright stance, the COP movement in the Anterio-Posterior (AP) direction is proportional to the horizontal acceleration of the CG. However, while the COP movement in the AP direction was in phase with CG movement, it was larger in amplitude. Similarly in the Medio-Lateral (ML) direction, COP movement was greater in magnitude than the CG movement, although the movements were anti-phase (Winter *et al.*). Intuitively, the COP will move more than the CG during sustained upright stance to maintain the CG position within the base of support. However, in the case of quiet stance, horizontal plane movements of the COP and the CG are very similar (Davis and Grabiner, 1996). Further, given the smaller COP movements of shooters relative to non-shooters (eg. Aalto *et al.*, 1990), CG and COP movement will be very closely related. As such, the use of COP would seem to be a reasonable measure of body sway for shooting research.

2.2.2 Rifle shooting and body sway

The effect of body sway on rifle shooting performance has been examined by a number of authors. This examination has taken the form of assessment during shooting in competition like conditions (eg. Era *et al.*, 1996; Norvapalo *et al.,* 1997) in rifle holding positions without shooting (eg. Bretz and Kaske, 1995; Niinimaa and McEvoy, 1983) and for quiet standing tasks (eg. Aalto *et al.*, 1990; Wu *et al.,* 1997).

In the only study to examine body sway during standing rifle shooting under competition conditions, Era *et al.* (1996) found that elite shooters produced significantly less body sway than novice shooters. Further, a hierarchical progression existed for body sway between different skill levels, with the better skill levels exhibiting less body sway. Four groups of shooters were tested: 6 international level men, 3 international level women, 8 national level men and 7 controls, termed naive shooters. Each shooter performed 100-200 shots over a distance of 18m. As such, competition conditions were compromised, as 18m is not a competition distance and more shots were taken than in competition. Although the calculations were not fully detailed in the article, posture control was assessed using the horizontal centre of forces (COF), which was obtained from an algorithm that incorporated the COP, body mass and 0.55 times body height. COF total path and mean speed in the X-axis (parallel with the line of shot) and Y-axis (perpendicular to the line of shot), the moment of velocity and the length of a square which encompassed all COF movement were calculated for the time between 7.5s before shot to the point of shot. It was interesting that Era *et al.* used both length and mean speed measures of COF, as speed is directly measured from length and values will be very closely related. A one way ANOVA found COF to be significantly different between the naive shooters and all other groups in the 7.5s preceding the shot, with larger COF speeds in X and Y axes and higher maximal speeds than the other groups, although no statistical values were reported. The top level male shooters showed the lowest COF X and COF Y speeds and the smallest moment of velocity, while female top level shooters had significantly better values than the national level men in all parameters except in COF Y speed. It is unclear in the article exactly which relationships were statistically significant. While differences were found between shooters of different levels of skill and body sway related to performance for shooters of lower skill levels, Era *et al.* (1996) found no relationship between body sway and performance in the elite level group. This relationship was examined by comparing the 20 best and 20 worst shots, as defined by the shot score and the coach's evaluation of the quality of the shot, of the elite shooting group. Results were evaluated on an individual and group basis. Two tailed t-tests showed no significant differences between COF measures during good shots and COF measures during bad shots for the group, nor individuals.

Changes in body sway during the aiming process were also examined by Era *et al.* (1996). COF measures were quantified for five 1.5s windows (from 7.5s prior to shot until the point of shot) for elite and non-elite standing rifle shooters. Era *et al.* report finding significant reduction in COF velocity in the AP direction as the moment of shot approached ($p<0.05$ for a paired t-test) for the elite male and female shooters. This was not the case for the national level men or novice shooters. Novices were of particular note in that the COF velocity remained similar for all windows.

A number of factors may have affected the findings of Era *et al.* (1996). The elite group exhibited very little within group variability, minimising the likelihood of a correlation between body sway and shooting performance. This is a problem that exists in most research into elite level sports. Further, group numbers were low, reducing the statistical power of the study. Era *et al.* also reports using a 16-bit ADC board, the DT2821. However, according to the Data Translation (1996) catalogue the DT2821 board offers only 12-bit ADC. Given the minimal COP ranges of movement that are produced by rifle shooters, 12-bit ADC may not be precise enough to measure any differences in movement that may occur between shots in the elite group. An analysis of 12-bit and 16-bit ADC will be conducted as part of this study.

While no other studies have examined standing rifle shooting during competition, Norvapalo *et al.* (1997), examining running target shooters, found a similar tendency for novices to sway more than top level shooters. Total displacement and speed of the COP in the X-axis (parallel to the line of shot) and Z-axis (perpendicular to the line of shot) were calculated for the aiming phase (between 2 and 4s in length) of 30 slow running target shots from 10m. Three groups were tested: top level (international) shooters, national level shooters and novice shooters. A one way ANOVA showed that national and international level shooters had significantly lower COP velocities than novices in both X ($F=8.42$, $p<0.05$) and Z ($F=12.97$, $p<0.05$) axes. However, unlike Era *et al.* (1996), there was no difference between national and international level shooters. No data values were reported. Norvapalo *et al.* suggested this may be due to the use of only slow moving targets. Also, the national level group was older and therefore more experienced. Both factors may have served to minimise the difference between the groups.

Viitasalo *et al.* (1997) also failed to find significant correlations between body sway and shot performance for elite running target rifle shooters. Viitasalo *et al.* examined three groups of shooters in running target rifle shooting: international level rifle target shooters, regional level rifle target shooters and moose hunters. A definition of moose hunters was not provided. Each subject performed 30 slow run target shots while COP was calculated in the X-axis (parallel to the line of shot) and Z-axis (perpendicular to the line of shot) axis. When all shooters were analysed as one group, shooting performance was significantly correlated with COP amplitude, or range (X-axis, $r=-0.620$, $p<0.01$ and Z-axis, $r=-0.819$, $p<0.001$), indicating that as COP amplitude increased, shot score decreased. However, as for Norvapalo *et al.*

(1997), when groups were treated separately, no within group significant relationships were found. Viitasalo *et al.*(1997) suggest that there are factors other than body sway, such as unstable trigger squeezes, that influence shooting performance at the elite level. These factors will affect the strength of the relationship between body sway and performance. In both studies, the elite group comprised only six subjects, providing poor statistical power, with an r value in excess of 0.81 required for significance at $p<0.05$.

Similar to results found in rifle shooting research, differences in COP measures have been found between elite and non-elite archers but not between the elite archers themselves, nor between good and bad shots (Mason and Pelgrim, 1986; Squadrone and Rodano, 1995). Archery is a sport that holds strong similarities with shooting, with participants maintaining an upright, stationary position and shooting at a target, which requires extreme precision for good performance. Mason and Pelgrim (1986) tested elite level archers during simulated competition conditions while standing on a force plate. Body sway in the last second before shot, as measured by COP displacement range, COP standard deviation, and velocity in COPX and COPY, was compared with performance. Mason and Pelgrim found a significant relationship existed between these parameters. Specifically, body sway parallel to the line of shot (COPy) was related to the position of the arrow shot on target in the horizontal axis. However, this relationship was more significant for junior archers and not as apparent in senior archers. Mason and Pelgrim suggested that control of body sway was a prerequisite in becoming an elite archer, although once achieved, was not a discriminating factor of performance. Squadrone and Rodano (1995) also concluded that COP movement was not able to discriminate between elite level archers.

Rifle shooters have been found to not only be more stable than untrained shooters during shooting, but also during quiet standing (eg. Wu *et al.*, 1997; Viitasalo *et al.*, 1997; Aalto *et al.*, 1990). Norvapalo *et al.* (1997) compared competition (national and international level) and novice running target rifle shooters. COP amplitude (range) and average COP speed were calculated in the X and Z-axis (defined previously) from force plate data during normal standing for 30s. A one way ANOVA showed that COP amplitude was significantly smaller for competition shooters compared with novice shooters in the Z-axis ($F=8.60$, $p<0.05$) but not the X-axis in both shooting and free standing tasks. As mentioned previously, no body sway data was reported in this article.

Aalto *et al.* (1990) found that both rifle and pistol shooters swayed less than untrained subjects during quiet stance over a period of 27s. These tasks performed by shooters and controls (non shooters) involved standing on a custom built force plate for 180s, the first 90s with the eyes open and the second 90s with eyes closed. Average COP velocity was calculated from six 27s periods within this time, three in each 90s period. Using Wilcoxon's rank sum test, significantly reduced average COP velocities were found in the shooter group compared to the control group. Aalto *et al.* suggest that this was due to specific training of postural control in these shooters.

Conversely, Niinimaa and McEvoy (1983) found no difference between the COP excursions (total distance the COP travels) for shooters and untrained subjects during a 60s standing task. Four groups, comprising elite rifle shooters, elite biathletes, intermediate level rifle shooters and a group of non-shooters were tested. Subjects stood on a force plate, while holding a rifle in a shooting position, both before and immediately after exercise. COP excursions tended to decrease with an increase in shooting experience but were not found to be significantly different between groups.

However, a number of major limitations existed in the Niinimaa and McEvoy (1983) study. Subject numbers in each group were very small (N=4 to 6) reducing statistical power. Force plate measurement was performed using a 12-bit ADC system, which increases the potential error due to quantisation in the measure. Further, while COP length measures can be influenced considerably by noise, particularly over long measurement periods (Granat *et al.*, 1990), no smoothing seems to have been used. These factors cast doubts over the reliability and usefulness of this finding.

The premise in assessing postural sway by using these tasks is that they relate to performance, or body sway during performance. This was also specifically examined by Viitasalo *et al.* (1997), who measured COP amplitude (range) for three groups of shooters (international level, national level and moose hunters) during a 30s standing trial with eyes open and a 30s trial with eyes closed and correlated these parameters with shooting performance. When all shooters were analysed as one group, shooting performance was significantly correlated with COP amplitude during standing with eyes open (X-axis $r=-0.630$, $p<0.01$, Z-axis $r=-0.692$, $p<0.01$) and standing with eyes closed (Z-axis only $r=-0.536$, $p<0.05$). These results indicated that lower COP amplitudes were associated with better performance. Also, in the Z-axis, COP amplitude during shooting was significantly correlated with COP amplitude during standing with eyes open ($r=0.828$, $p<0.001$) and standing with eyes closed ($r=0.739$, $p<0.001$). When groups were analysed separately, no significant relationships existed between performance and COP amplitude for any task. However, COP amplitude in the Z-axis during shooting was related to COP amplitude during eyes open stance ($r=0.775$, $p<0.05$) and eyes closed ($r=0.830$, $p<0.05$). Viitasalo *et al.* suggested that the ability to maintain stable posture in eyes open and eyes closed conditions was a good predictor of stability during shooting.

In summary, the influence of body sway on rifle shooting performance has been shown to be significant when shooters from a wide range of skill levels were used (eg. Norvapalo *et al.*, 1997). Further, elite level shooters have been shown to be more stable than novice shooters (eg. Era *et al.*, 1996). However, the link between performance and body sway for elite shooters has not been found to be significant (eg. Viitasalo *et al.*, 1997). Low subject numbers and poor measurement resolution may have affected these findings. As mentioned, stage 1 of this study will address the issue of resolution. The examination of the relationship between body sway and performance using greater measurement resolution than used in these studies will be the focus of section two.

2.2.3 Pistol shooting and body sway

In the few studies examining body sway and pistol shooting performance, results and conclusions have been conflicting. Mason *et al.* (1990) found significant associations between body sway and pistol shooting performance at the elite level. 16 elite level pistol shooters performed 25 shots under simulated competition conditions. A large number of parameters were measured and calculated relating to body sway, aim point fluctuation, pistol movement and grip pressure. In multiple regression analysis including all parameters, body sway, as measured by COP range, was found to be the factor most influential to shot result, contributing 30% (R=0.55, p<0.02) to errors of shot on target, with total pistol movement accounting for the next largest variance of 13%. On examination of the influence of these variables to errors of shot in horizontal and vertical axes, it was found that COP range parallel to the line of shot was correlated with the vertical fall of shot on the target (above and below the target centre, r=0.63, p<0.01).

A limitation of the Mason *et al.* (1990) study was the use of 12-bit ADC for force plate data collection for body sway assessment, a limitation also present in rifle shooting research as mentioned in section 2.2.2. The measurement resolution and error due to quantisation using 12-bit ADC may be a limitation of measure of body sway for pistol shooters. Given the elite nature of the group tested by Mason *et al.*, it is likely that the difference in body sway values for different shooters was small. The poor resolution and potentially large error due to quantisation in body sway measures will limit the ability to discern between shooters on this basis. As such, it could be expected that statistical analyses would be influenced by this data, potentially masking relationships that exist or finding relationships where they do not exist.

However, Iskra *et al.* (1988) also concluded that body stabilisation is the most important factor in pistol shooting performance, supporting the findings of Mason *et al.* (1990). Spectral analyses were performed on signals recorded from accelerometers fixed to the gun barrel and gun butt. Seventeen shooters performed a number of shots on target. These subjects included one shooter who was described as an expert (not well defined by the researcher). The level of skill of the remaining 16 was not reported. A mean power spectrum, obtained by averaging individual shot power spectra across all trials for each shooter, showed three resonance peaks (figure 2.2). The first peak (0.7Hz) correlated with the shot result, although it is unclear from the article how this correlation was obtained. Iskra *et al.* attributed this frequency to body sway. A number of authors have shown that the majority of power in COP movement during quiet stance exists below 1.2Hz (eg. Soames and Atha, 1982; Lucy and Hayes, 1985; Powell and Dzendolet, 1984), with peaks below 1Hz during quiet stance. Given that the pistol-shooting stance is an example of quiet stance, these peaks could be expected to exist in shooters also. As such, the conclusion of Iskra *et al.* seems reasonable. A second peak was found reported at the 7Hz mark, although the example frequency graph presented indicated this peak was between 4Hz and 5Hz. The authors could not explain this peak. While slightly lower than the value reported by Iskra *et al.*, peaks between 4 and 5Hz have been found in force plate data during quiet stance that were attributed to the ballistocardiogram (Goldie, 1985) and may be a contributing factor to this 7Hz peak. Alternatively, it could be associated with muscle tremor. Thomas and Whitney (1959) report that muscle tremor existed in force plate signals between 5Hz and 10Hz. However, Iskra attributed the third peak (12Hz) to muscle tremor. The generating mechanisms of these peaks at higher frequencies are unclear but would seem to be too high to be associated with body sway, and will be of less interest to this study.

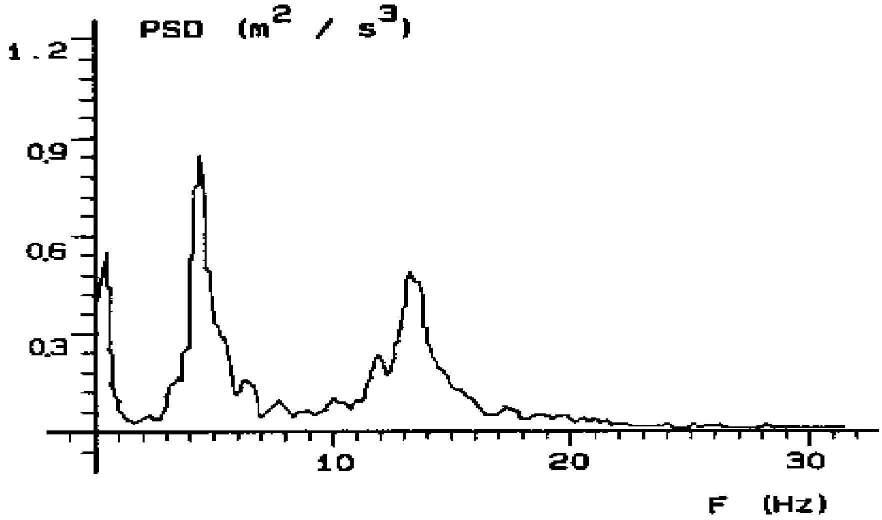


Figure 2.2: Power spectral graph presented by Iskra *et al.* (1988) showing peaks at <1Hz, 5Hz (although 7Hz reported in the text) and 12Hz.

Iskra *et al.* (1990) also reports that the finding that body sway is the most influential factor to shooting performance supported a number of previous studies (Losel, 1976; Radowski, 1975; Rudina and Bik, 1978). These articles could not be obtained and translated in the time span of this study. It should be mentioned that, while correlations performed by Iskra *et al.* indicated that body sway and shot result were associated, the conclusions of Iskra *et al.* were not well developed. Body stabilisation would seem to be a factor affecting performance in this study, although the measurement of body sway using accelerometers on the gun is somewhat indirect.

In contrast to the findings and conclusions of these studies, Aalto *et al.* (1990) suggested that body sway is unimportant for pistol shooting. Aalto *et al.*, examined posture control of two pistol shooters, eight rifle shooters and 27 control subjects during 27s stability tasks. Results indicated that the rifle shooters were more stable than pistol shooters. Aalto *et al.* report that this difference was statistically significant, although no statistical values were reported. Based on these results, Aalto *et al.* suggested that this result supported the 'commonly held notion' that body sway was not important to pistol shooting performance. Given only two pistol shooters were used, this conclusion seemed a little presumptuous. Further, the stability test used was not specific to shooting and no link between stability tasks and posture control during shooting was made. Certainly, this notion does not appear to hold up based on the research by Mason *et al.* (1990) and Iskra *et al.* (1988).

2.2.4 General posture control

There is a large body of literature associated with human postural control covering a large number of sub topics. This next section will briefly review a selection of these topics.

Research in posture control has covered a wide range of issues, including normal stance (eg. Stevens and Tomlinson, 1971; Murray *et al.*, 1975; Ekdahl *et al.,* 1989), sites of posture control (eg. Horak and Nashner, 1986; Nakagawa *et al.*, 1993; Teasdale *et al.*, 1993), modelling of stance (eg. O'Riley *et al.*, 1990; Davis and Grabiner, 1996) and clinical applications (eg. Lucy and Hayes, 1985; Simoneau, 1992; Bauer, 1993).

Measurement of sway and postural control has been performed using both kinetic and kinematic methods. Early kinematic methods included direct attachment of wires between the upper and lower back of a subject and a recording device to monitor the amount of movement experienced at these two sites (Stevens and Tomlinson, 1971). Studies have digitised body landmarks from film or video to quantify sway (eg. Brown and Frank, 1997). However, the most common method used to measure postural control has involved locating the subject on a single force plate and monitoring COP movement during a specified time. This is the method almost exclusively used in shooting research to measure posture control.

Different researchers have used a number of parameters to quantify posture control and stability. COP movement is most often quantified in terms of displacement, velocity, area covered per unit of time and variability in the AP and ML axes (eg. Gianikellis *et al.*, 1995; Landin *et al.,* 1993). Other forms of measurement, such as the variability of force in the ML and AP directions (Goldie *et al.*, 1994) and Fourier analysis have also been used (eg. Powell and Dzendolet, 1984; Liu and Lawson, 1995).

There is contention as to the most valid and reliable measure for posture control, with advantages existing for each measurement type. Goldie *et al.* (1989) performed a reliability study using 28 subjects, found that the variance in the horizontal force signals (ML and AP directions) was a more reliable measure than variance in COP, particular for one-legged stance. Simoneau (1992) reported finding that COP measurement was unreliable in posture assessment. Samson and Crowe (1996) found inconsistencies across trials for the length of the COP trace, as well as poor COP repeatability between stability trials. Despite these concerns, COP remains the most widely used measure of posture assessment. Possible reasons for this lack of reliability of COP parameters, a focus of this study, is the use of 12-bit ADC systems.

Numerous researchers have examined the posture control strategies used to maintain upright stance. Horak and Nashner (1986) suggested that sway in the AP and ML directions was regulated by different mechanisms. Sway in the AP direction is controlled by an ankle strategy, while sway in the ML direction was controlled by a hip strategy. Using the ankle strategy, body position is controlled by alternately activating and deactivating the musculature on the anterior and posterior aspects of the ankle and leg. Sway in this direction has been modelled as an inverted pendulum (Nashner and McCollum, 1985). Pivoting about the ankle joints, the body acts as a single segment and sways back and forth similar to a pendulum. This inverted pendulum has been included in models of quiet stance (eg. O'Riley *et al.*, 1990; Davis and Grabiner, 1996). The hip strategy used in ML sway control involves the hip musculature working to keep the CG at or about the centre of balance (COB) by loading or unloading each hip. Winter *et al.* (1993) examined the different strategies more closely using two force plates, one for each foot. Winter *et al.* report that AP and ML sway control are independent of each other. Confirming previous research, Winter *et al.* also suggested that musculature about the ankle controlled only the AP sway, while hip adductors/abductors were the main muscles used in the control of ML sway.

Winter (1995) suggested that balance and posture are controlled by three systems in the body.

(1) Vision provides information on the position of the body relative to the external environment, the position of body parts relative to each other, and spatial orientation of the body and environment.

(2) The vestibular system acts as a level balance mechanism, providing information on head position and acceleration, and assisting with the provision of a stable visual image.

(3) Afferent information, provided by the somatosensory system, monitors body segment orientation, joint position and joint angular movement.

In addition, Deitz *et al.* (1992) suggest the golgi tendon organs may also be involved in posture control by way of assisting with body weight and gravity, possibly locating the body's CG.

Cavanagh *et al.* (1993) report that, while these three mechanisms are complimentary to each other, they each have a specific role. The afferent information from the somatosensory system is highly redundant, but useful in a number of different environments or where the effectiveness of the other systems is reduced or eliminated. Such a situation exists in shooting, where much of the visual system is associated with the aiming process. Nakagawa *et al.* (1993) suggested that the somatosensory system contributed little to the control of body sway. Simoneau (1992), however, reports that somatosensory input is the most important of the three, contributing 40% to the control of balance, followed by vision (29-34%) and vestibular apparatus (3%).

Balance in normal, healthy individuals has been examined by a number of authors. Murray *et al.* (1975) in one of the earliest posture assessment studies using a force plate, noted that the COP is constantly moving and traces a long path while remaining within a small radius. During double limb stance over 30 seconds, COP ranges of 3.8mm in the AP direction and 3.3 mm in the ML direction were reported. These values are similar to the COP ranges reported by Ekdahl *et al.* (1989) of 3-4mm for 20 - 29 year old subjects. However, Simoneau *et al.* (1992) reports finding very large COP ranges of up to 16mm for normal subjects using a similar protocol and force plate system to that used by Ekdah*l et al.*. It is unclear what has caused this large discrepancy between studies.

The effects of changed conditions on posture, such as eliminating visual feedback by closing the eyes or altering the support base by balancing on one leg have shown consistent results with increases in postural sway always found under these conditions. Bretz and Kaske (1995) found an increase in the area of the COP trace during eyes closed conditions when compared with eyes open for a double stance stability test. Goldie *et al.* (1989) found an increase in the variability of horizontal forces and COP, as measured by a force plate, under similar conditions. These results support the theory that visual cues form a major role in stability.

It is unclear from the literature how anthropological factors affect stability. Powell and Dzendolet (1984) examined the influence of height, weight, a number of foot dimensions, height of the ankle and height of the umbilicus of 80 adult male subjects on body sway. No link was found. Ekdahl *et al.* (1989) also found no relationship between subject height, weight and COP excursion. However, Chia *et al.* (1993) found height to influence stability results for both experimental and control group. This area needs more research to define the relationship between anthropological measures and body sway. Although not examined in this study, these factors may also have implications for shooters as the body gun system will be different between subjects of different anthropology. However, this is beyond the scope of this study.

Spectral analyses of body sway measures have been performed by a number of researchers. The majority of these studies have calculated the COP in AP and ML directions and used a fast Fourier transform (FFT) analysis to obtain a mean power spectrum of the COP signal. Most power during quiet stance seems to be less than 3Hz, with peak power at approximately 0.1-0.3Hz (Scott and Dzendolet, 1992; Liu and Lawson, 1995; Soames and Atha, 1982). Bretz and Kaske (1995) found dominant frequency of sway in both the ML and AP direction was 0.45Hz, although there were higher frequencies observed in the AP direction. Lucy and Hayes (1985) report finding the principal power of COP less than 1Hz in both AP and ML directions, with peak power less than 0.2Hz. Mean power was higher for subjects with cerebral ataxia, with peaks above 1Hz. Lucy and Hayes also noted some higher frequency components (1-3Hz) for some of the older subjects, suggesting that this result was linked to the degradation of the peripheral sensory system. Simoneau (1992) also reported an increase in the mean frequency of COP movement in patients with diabetic neuropathy compared with healthy subjects. No frequency analysis of force plate data has been performed in shooting.

To adapt some of these findings to shooting and summarise this section, body sway during shooting may originate from a number of sources. The natural tendency of the body to sway while standing as well as the requirements of movement generated from the aiming process will affect the amount of movement generated by body sway during shooting. Muscle cannot, by its nature, maintain a totally constant tension (Lees, 1986). As such, reliance on musculature to maintain posture will cause at least a small amount of movement. Patla (1997), reported that the threshold for excitation of the kinaesthetic receptors is not reached during quiet standing, suggesting that body stiffness, controlled actively by muscles surrounding a joint and passively by other structures, is ‘set’ which provides the necessary stability to remain still. It is possible, then, that inaccurate settings of this ‘body stiffness’ may allow for more body sway. Physiological tremor, such as breathing and heartbeat, also influences overall body movement (Mason and Bond, 1990). Although respiration has been shown to influence body stability (Takata, Kakeno *et al.*, 1983), shooters hold their breath in the preceding seconds before shot to eliminate this influence on stability.

A number of aspects of the shooting skill may influence where and how posture is controlled during shooting. Era *et al.* (1996) suggested that the visual system is almost exclusively involved in the aiming process and would contribute little to balance, as did Aalto *et al.* (1990). Cavanagh *et al.* (1993), as mentioned previously, reported that the somatosensory system information is useful where the effectiveness of the other systems is reduced. Aalto *et al.* (1990) found that the ratio between stability with eyes open and eyes closed was smaller for shooters than for control subjects. Aalto *et al.* concluded that shooters rely less on vision for postural control, and compensates with proprioceptive and vestibular feedback. However, as mentioned, Patla (1997) reported that the threshold for excitation of the kinaesthetic receptors is not reached during quiet standing. This being the case, the contribution from the somatosensory (proprioceptive) system may be limited. More accurate settings of body stiffness, as proposed by Patla as controlling sway in quiet standing, may be the mechanism that has been trained to a high level by elite shooters, which contributes to the highly stable stances.

2.3 Aiming

2.3.1 Rifle shooting and aim point fluctuation

Aim point fluctuation refers to the movement of the point of aim of the gun on the target and relates directly to shooting performance. There are a number of commercial laser or infrared based systems available that perform the task of monitoring the aim point of the gun on the target. These systems consist of an instrumented target that outputs beams, which are detected by a directional sensor located on the barrel of the gun. The sensor is aligned such that the direction of the sensor corresponds with the point of aim of the gun on the target. This aim point measurement is calibrated and quantified in terms of the vertical plane XY co-ordinates of the target and fed into a computer. The vibration of the gun at the point of shot is detected to locate the moment in time that the shot is fired. Figure 2.3 shows the aim point fluctuation on a target as recorded by the laser-based SCATT system.

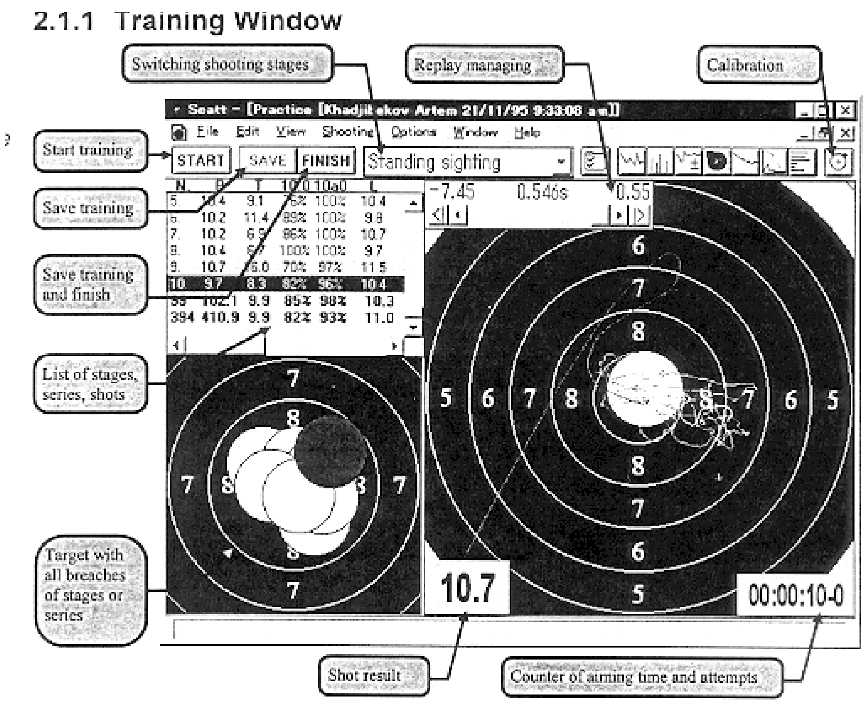


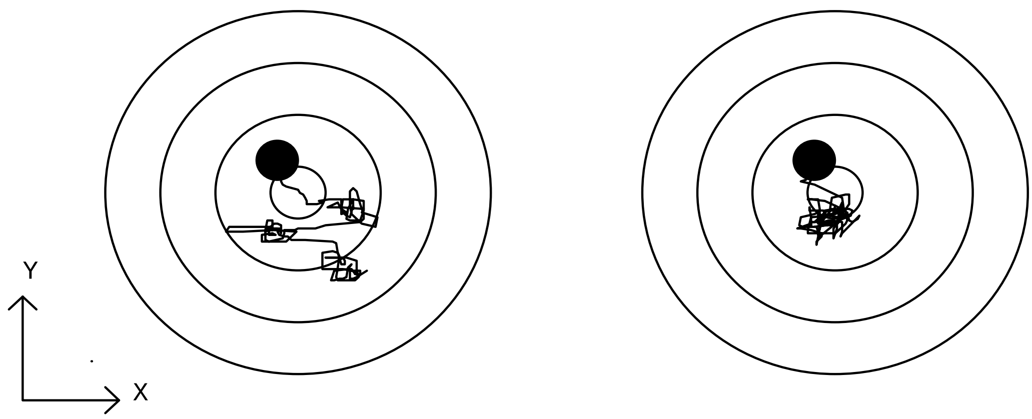
Figure 2.3: SCATT (aim point fluctuation) output. The fluctuating line represents the aim point (measured every 1/128 s), the large dots represent the aim point at the instant the shot was fired.

The aiming process during shooting has been examined with the use of these laser-based systems (Zatsiorski and Aktov, 1990; Lenart, 1992; Mason *et al.*, 1990). Zatsiorski and Aktov (1990) monitored the aim point of elite rifle shooters during the five seconds preceding the shot. The researchers found that general fluctuations of this aim point, quantified by measuring the size of a rectangle fitted around all aim point positions recorded, decreased as the instant of shot approached. Further, in the last second before shot, the aim point always remained within the ‘9’ ring. Interestingly, while the vertical fluctuations of the aim point decreased as the point of shot approached, the horizontal deviations remained fairly constant. Due to small subject numbers, no statistical analysis between aim point fluctuation and shooting performance was reported in the Zatsiorski and Aktov study.

Zatsiorski and Aktov (1990), in further examination of the aim point fluctuation in elite rifle shooters, found that a 'fixation strategy' was used by elite shooters in preference to an 'interception' technique when aiming at a target. This fixation strategy involved stabilising the aim point at a single point or number of points on the target, finally centring on the target centre. The interception technique involved moving the aim point across the target. Shooters would attempt to 'time' the point of shot such that the aim point coincided with the point of intersection with the target centre. It is not clear from the study if any shooters used the interception technique.

The fixation and interception techniques were also recognised by Heinula (1996), although different terms were used to describe them. In a technical report on aim point fluctuation, Heinula collected a large amount of aim point data on over 100 shooters over three years. Shooter skill levels included international, national, club and untrained shooters. Based on the stability of the aim point hold, Heinula formulated three aim point categories for shooters; hold shooters, reaction shooters and optimised shooters. Hold shooters were the same as fixation shooters and reaction shooters were the same as interception shooters defined by Zatsiorski and Aktov (1990). Optimised shooters lay between the hold and the reaction shooters, exhibiting some stability of aim point hold, but still requiring timing of the shot as the aim point passed across the target centre. Heinula reports that most shooters employed the hold technique, although many alternated between the three categories presented.

Zatsiorski and Aktov (1990) noted that the fixation strategy used by elite shooters when aiming could be broken down into two categories, although no cluster or other statistical analysis was performed on the data. As shown in figure 2.4, one cluster of shooters stabilised around a point, which was not necessarily the centre of the target, as the instant of shot approaches. This would then be repeated 2 to 5 times, with the shooter stabilising on one point for a period, then moving to another and stabilising again. The second technique evident was a single stage aiming process, where the shooter would stabilise on one point only. Also, a consistent approach on the target was noted for each shooter, with six of the ten shooters tested levelling their rifles predominantly up and down while four levelled right to left.



(i) Series of small areas of aim (ii) One aim area only

Figure 2.4: Representation of the two aim variants during the aiming process found by Zatsiorski and Aktov, 1990.

Heinula (1996), from the large body of data the researcher collected, formulated an aim point model and a regression equation of both pistol and rifle shooting performance. This was based on three aiming factors: the hold, the aim and trigger control. The hold was defined as the steadiness of the aim point about a central point, the aim was defined as the proximity of the aim point to the centre of the target, and the trigger control was defined as the ability to press the trigger without the aim point moving. It was reported that the quality of the hold was the major contributing factor to shooting performance, accounting for 83% of the variation in scores for a given shooter. Unfortunately, Heinula does not define the exact method of calculation of these factors in the research paper.

As for body sway, researchers have found significant relationships between aim point fluctuation and shooting performance when examining groups with a range of skill levels, but not within the elite level shooting groups. Viitasalo *et al.* (1997) tested 22 subjects from three groups, international shooters, regional shooters and moose hunters, during the performance 30-60 shots on slow running targets while aim point fluctuations were monitored. Aim point amplitude, interpreted by this researcher as range, and result of shot on target was quantified. Shooting performance and aim point fluctuation was significantly correlated in the X, or horizontal, axis ($r=-0.636$, $p<0.01$) and Y, or vertical, axis ($r=-0.712$, $p<0.001$) when all shooters were analysed together. However, when the group analysed was separated into the individual groups tested, statistical analyses were not significant, although only six elite shooters made up this group, providing very low statistical power, with a value of $r>0.81$ required for significance at $p<0.05$. Norvapalo *et al.* (1997), in a similar study, found a progression from novice shooters to national shooters to international shooters for aim point fluctuations, with the novices producing the most fluctuation and the international shooter the least. This was found for both horizontal and vertical aim point fluctuations. However, as for the Viitasalo *et al.* study, no statistical significance was found between performance and aim point fluctuation when the elite level group was treated separately. Once again, only six elite shooters made up this group, reducing statistical power.

A limitation of the quantification of aim point fluctuation in both the Viitasalo *et al.* (1997) and Norvapalo *et al.* (1997) study did not take into account different aim point strategies that may have existed in the data. Range measures alone will not be sensitive to the aim point strategies detailed by Zatsiorski and Aktov (1990) and Heinula (1996). As such, these strategies will influence any statistical analysis of the relationship between aim point movement, as measured by range, and performance. Further, Heinula reports shooters that used a range of strategies, which will further cloud any statistical analysis on a group basis.

2.3.2 Pistol shooting and aim point fluctuation

Pistol shooting performance and aim point fluctuation was examined by Mason *et al.* (1990) with a weak linear relationship between the two reported ($r=0.2$, $p<0.05$). The quantification of aim point fluctuation in the Mason *et al.* study was limited to length of movement and shot position in horizontal and vertical directions. A more thorough analysis of the aim point movement, including quantification of areas of movement, may have assisted in defining this relationship better. Further, the different aim point strategies found by Heinula (1992) in both rifle and pistol shooters would have influenced this result, largely negating any statistical analysis that was conducted across the group.

There are no other studies examining performance and aim point fluctuation in pistol shooting.

2.4 Body sway and aim point fluctuation

2.4.1 Body sway and aim point fluctuation in rifle shooting

No studies have examined the relationship between body sway and aim point fluctuation in standing rifle shooting.

Aim point fluctuation and body sway have been found to be related in running target rifle shooting. Viitasalo *et al.* (1997) compared body sway and aim point oscillations. Aim point length in the vertical direction was correlated with COP amplitude in the X-axis (parallel with the line of shot, $r=0.534$, $p<0.05$) and Z-axis (perpendicular to the line of shot, $r=0.536$, $p<0.05$). It was interesting that body sway in both axes related to an increase in aim point movement in the vertical axis only. This relationship did not exist for the elite level shooters when they were examined as a sub group. As mentioned previously, with only six shooters, statistical power was low. Further, the description of aim point fluctuation was limited to ranges and no account for aim point strategies was made. Norvapalo *et al.* (1997) found that elite level shooters were more stable and exhibited less aim point fluctuation than national level or novice shooters during running target rifle shooting. However, these parameters were not directly compared in the report nor was the data presented, and only discussed in general terms.

2.4.2 Body sway and aim point fluctuation in pistol shooting

No studies have examined the relationship between body sway and aim point fluctuation in pistol shooting. A broad link might be indicated in the comparison of

COP and aim point movement in their respective axes. Mason *et al.* (1990) reported more aim point fluctuation in the horizontal direction (108.9mm) as compared with the vertical direction (89.2mm), while body sway across the line of shot (3.3mm) was larger than parallel to the line of shot (3.0mm). Body sway perpendicular to the line of shot (as measured by COPx), without compensation from body parts, will cause a horizontal movement of the aim point across the target. Hence the larger amount of sway perpendicular compared to parallel to the line of shot may be linked to greater horizontal compared with vertical aim point movement. With more accurate body sway data and a larger number of aim point parameters, the relationship would be better defined.

This study will examine more closely, the relationship between aim point fluctuations and body sway, as well as the relationship each has to shooting performance in standing rifle and pistol shooting.

CHAPTER 3 OBJECTIVES OF INVESTIGATION

3.1 General Aims

(1) To assess the limitations associated with quantisation using 12-bit ADC and 16-bit ADC systems with respect to COP and force measures for shooting.

(2) To explore the relationship between body sway, aim point fluctuation and performance in rifle and pistol shooting.

3.2 Specific Aims

Stage 1

(1) To assess the effects of quantisation on COP measurement in terms of :

a. quantisation error

b. measurement step

(2) To compare 12-bit ADC and 16-bit ADC force plate data collection in terms of:

a. quantisation error in a single measure

b. measurement step

c. data collected from trials

(3) To compare the quantisation error and measurement steps for body sway parameters used in this study using 12-bit ADC and 16-bit ADC.

Stage 2

(4) To quantify 21 body sway parameters of rifle and pistol shooters and assess the most appropriate to use in measurement of body sway.

On a group and individual basis

For Rifle Shooters

(5) To determine the relationship between COP movement (as a measure of body sway) and shooting performance.

(6) To determine the relationship between aim point fluctuation and shooting performance.

(7) To determine the relationship between COP movement and aim point fluctuation.

For Pistol Shooters

(8) To determine the relationship between COP movement (as a measure of body sway) and shooting performance.

(9) To determine the relationship between aim point fluctuation and shooting performance.

(10) To determine the relationship between COP movement and aim point fluctuation.

3.2.1 Hypotheses

Aim 5: Null Hypothesis

No significant relationships exist between body sway and shooting performance.

Aim 6: Null Hypothesis

No significant relationships exist between aim point fluctuation and shooting performance.

Aim 7: Null Hypothesis

No significant relationships exist between COP movement and aim point fluctuation.

Aim 8: Null Hypothesis

No significant relationships exist between body sway and shooting performance.

Aim 9: Null Hypothesis

No significant relationships exist between aim point fluctuation and shooting performance.

Aim 10: Null Hypothesis

No significant relationships exist between COP movement and aim point fluctuation.

CHAPTER 4 METHODS

4.1 Stage 1: Assessment of the limitations of 12-bit and 16-bit ADC

12 and 16-bit ADC force plate data were examined both theoretically and experimentally.

4.1.1 Theoretical assessment

Limitations of 12 and 16-bit ADC were explored in three ways. For sections 4.1.1.1 and 4.1.1.2, data from the AMTI LG6-4 and the Kistler 9287A force plates were analysed. Section 4.1.1.3 only included the AMTI LG6-4.

4.1.1.1 Propagation of quantisation error in COP calculations

The calculation of COP involves using data from a number of force plate channels which all have quantisation error inherent in them. Taylor (1982) detailed a method for approximating measurement error that is propagated during calculations where a number of variables, each with their own error (in this case due to quantisation), are included in an equation. The error propagated in COP measurement was calculated using these techniques for 12-bit and 16-bit ADC data collection from the AMTI LG6-4 plate, the force plate used in this study, and the Kistler 9287A plate. Both plates have been used in posture sway measurement.

Using Taylor's (1982) techniques (summarised in this section), quantisation error was approximated for a single COP measure. The effects of quantisation error on single COP measures were explored in the following ways

a. Quantisation error in a single COP measure (AMTI LG6-4, Kistler 9287A)

b. Quantisation error in a single COP measure as Fz increases

b. Quantisation error in a single COP measure as Mx and My increase (Fx and Fy constant)

c. Quantisation error in a single COP measure as Fx and Fy increase (Mx and My constant)

Shooting data, obtained as for stage 2 (section 4.2), were used for the purposes of calculation.

Note: Calculation of quantisation error using Taylor (1982)

The basic principles are presented below. Full derivations of these methods are detailed in Taylor (1982).

- Uncertainty in sums and differences

  If $x_1 , \dots , x_n$ are measured with uncertainties (due to quantisation) $\delta x_i , \dots , \delta x_n$ and the measured values are used to compute:

  $$y = x_1 + \dots + x_m - (x_{m+1} + \dots + x_n)$$

  Then an approximation of the error propagated in the calculation is

  $$\delta y^2 = \delta x_1{}^2 + \dots + \delta x_m{}^2 + \delta x_{m+1}{}^2 + \dots + \delta x_n{}^2$$

  and the upper error limit (maximum possible error) will be

  $$|\delta y| = |\delta x_1| + \dots + |\delta x_m| + |\delta x_{m+1}| + \dots + |\delta x_n|$$

- Uncertainty in products and quotients

If $x_1, \ldots, x_n$ are measured with uncertainties (due to quantisation) $\delta x_i, \ldots, \delta x_n$ and the measured values are used to compute (* used here for multiplication sign for clarity):

$$y = \frac{x_1 * \ldots * x_m}{x_{m+1} * \ldots * x_n}$$

Then the fractional uncertainty of the error propagated in the calculation is

$$\left(\frac{\delta y}{y}\right)^2 = \left(\frac{\delta x_1}{x_1}\right)^2 + \ldots + \left(\frac{\delta x_m}{x_m}\right)^2 + \left(\frac{\delta x_{m+1}}{x_{m+1}}\right)^2 + \ldots + \left(\frac{\delta x_n}{x_n}\right)^2$$

and the fractional uncertainty upper error limit (maximum possible error) will be

$$\left|\frac{\delta y}{y}\right| = \left|\frac{\delta x_1}{x_1}\right| + \ldots + \left|\frac{\delta x_m}{x_m}\right| + \left|\frac{\delta x_{m+1}}{x_{m+1}}\right| + \ldots + \left|\frac{\delta x_n}{x_n}\right|$$

- Uncertainty in a measured quantity multiplied by an exact number

If x is measured with uncertainty (due to quantisation) δx and is used to compute:

$$y = C.x$$

Where C has no uncertainty, the upper error limit (maximum possible error) will be

$$|\delta y| = |C.\delta x|$$

NB Although not detailed in Taylor (1982), uncertainty in division by an exact

number was treated as for multiplication (ie. $\frac{x}{C} = \frac{1}{C} . x$)

- Uncertainty in a power

  If x is measured with uncertainty (due to quantisation) δx and is used to compute:

  $$y = x^n$$

  The fractional uncertainty upper error limit (maximum possible error) is given by

  $$\left|\frac{\delta y}{y}\right| \leq \left|\frac{n.\,\delta x}{x}\right|$$

  NB Although not detailed in Taylor (1982), uncertainty in roots were treated as for powers (ie $\sqrt{x} = x^{\frac{1}{2}}$)

- **NOTE:** Where variables are repeated in calculations, Taylor (1982) suggested that **quadrature summation** was a better approximation of error. For example:

  if y = x + xz

  then δy = δx + δ(xz)

  but, as x is repeated in the equation, will be better approximated by

  $$\delta y = \sqrt{(\delta x)^2 + (\delta xz)^2}$$

  For cases where variables were repeated in calculations, both maximum and approximate error have been calculated.

4.1.1.2 COP Resolution

Another method of examining 12-bit and 16-bit ADC is by comparing the COP measurement resolution each offers. During COP measurement during quiet stance, the force plate system effectively sets up a measurement grid with a resolution dependent on the body weight of the subject and the dimensions of the force plate. As such, COP is measured with measurement steps of a certain size. Approximate COP resolution, for 12 and 16-bit ADC was calculated for the AMTI LG6-4 plate and the Kistler 9287A plate using the formulas below:

$$COPx \text{ (measurement step)} = \frac{My(measurement.step)}{Fz(SubjectWeight)}$$

$$\text{COPy (measurement step)} = \frac{Mx(measurement.step)}{Fz(SubjectWeight)}$$

Note: Measurement step refers to the minimum increment or unit of measure.

These formulas were used as movement of COPx and COPy is influenced almost solely by the moments about the X and Y axes (Mx and My). In quiet stance and particularly in shooting, Fz will remain almost constant and Fx and Fy values will be minimal.

To expand; Fz is the sum of the weight of the body and gun system and should vary minimally due to body sway during shooting. Experimental data in this study (Appendix D) indicated that only small amounts of activity existed in the frequencies where body sway signal might be expected to exist (below 3Hz). While strong signals were present above this frequency, these signals were interpreted as being generated by noise and signal produced by shooters that was not associated with sway and will be eliminated by smoothing. The effects of Fx and Fy on COP are extremely small, given that the force values are small during shooting, with group means in this study of between 0.64N - 1.69N found (section 5.2.1). This already small value is further reduced in COP calculations as Fx and Fy are multiplied by a small constant (eg. 0.0535m in the case of the AMTI LG6-4 force plate). Lucy and Hayes (1985) report the effects of Fx and Fy on COP movement as being less than 1%.

Further, as shown in the error calculations previously, Fx and Fy will have very little influence on the error in COP calculation for the force and moment values produced during shooting.

To explore the differences in resolution under different condition, approximate resolutions were calculated using Fz from 500N-1100N.

4.1.1.3 Error and resolution of parameters used in this study

The error and resolution calculations in the previous sections were for single COP measures only. However, the majority of postural sway measures in shooting and other applications involve monitoring COP over a set period of time.

As such, error estimates using Taylor's (1982) techniques and resolutions were calculated for each of the body sway parameters used in this study (as detailed in table 4.2.3 in section 4.2.5).

4.1.2 Experimental assessment

Force platform data were collected using 12-bit and 16-bit ADC for one pistol shooter during the performance of three shooting trials and for two trials with a 750N weight placed on the force plate. All conditions and apparatus are described in section 4.2, with the exception that, after the signal was passed through the amplifiers, it was directed to two systems for sampling; one 12-bit ADC and one 16-bit ADC system.

4.2 Stage 2: Body sway and aim point during shooting

4.2.1 Participants

Participants were elite level air pistol and rifle shooters, currently in the Australian National Squad. General participant details are summarised in Table 4.2.1.

Table 4.2.1: Details of shooters participating in this study

		No. of shooters	Age (years)	Mass (kg)
Pistol	(1M,4F)	**5**	**27.2±8.7**	**72.3±17.0**
Rifle	(4M,2F)	**6**	**22.2±2.6**	**89.7±12.2**

M = Male, F = Female

Due to the small numbers of shooters, male and female shooters were treated as one group.

4.2.2 Task

After thorough familiarisation with the laboratory and testing conditions, shooters performed a number of tasks during the testing session.

Shooters were asked to complete 20 shots as if in competition. This included as many sighting shots as desired. Time limits corresponding to competition shooting were applied to each shooter. In true competition, males shoot 60 shots within 1 hour 45 minutes while females shoot 40 shots in 1 hour fifteen minutes. Shooters were required to work within the equivalent time frame (ie. males had 35 minutes to complete 20 shots, females had 37.5 minutes).

Rifle shooters performed this task with full competition clothing, which included stiff leather jacket and pants, gloves and wide, flat soled boots. This clothing was used by each shooter in competition and complied with shooting clothing rules. Pistol shooters performed in clothing they typically wore in competition. Unlike rifle shooters, pistol shooters do not wear special clothing during competition.

No live ammunition was used during testing. Gas cylinders were primed and released, providing similar noise associated with the shot but with a reduced recoil.

4.2.3 Laboratory Set-up

Testing was conducted in the Biomechanics Laboratory, Victoria University (City Campus), Melbourne, Australia.

The laboratory was set up to simulate shooting competition conditions. All shooting tasks were performed under simulated competition conditions. These conditions included the allowable body and gun position from which to shoot, the type of gun used, clothing restrictions and lighting conditions. A target was set 10m from the shot line, with the centre of the target set to a height of 1.45m from the ground. The target was brightly lit by room lighting and spotlights around the target area. Targets used were official Shooting Association cardboard targets for 10m rifle and pistol shooting.

A table was located at the ten metre mark (shot line) immediately in front of the shooter, as provided in competition.

The 10m (shooting line) mark was located approximately 0.3m from the front edge of a force plate such that each shooter would take their shooting position near the centre of the force plate. An overview of the laboratory set-up is presented in figure 4.2.1.

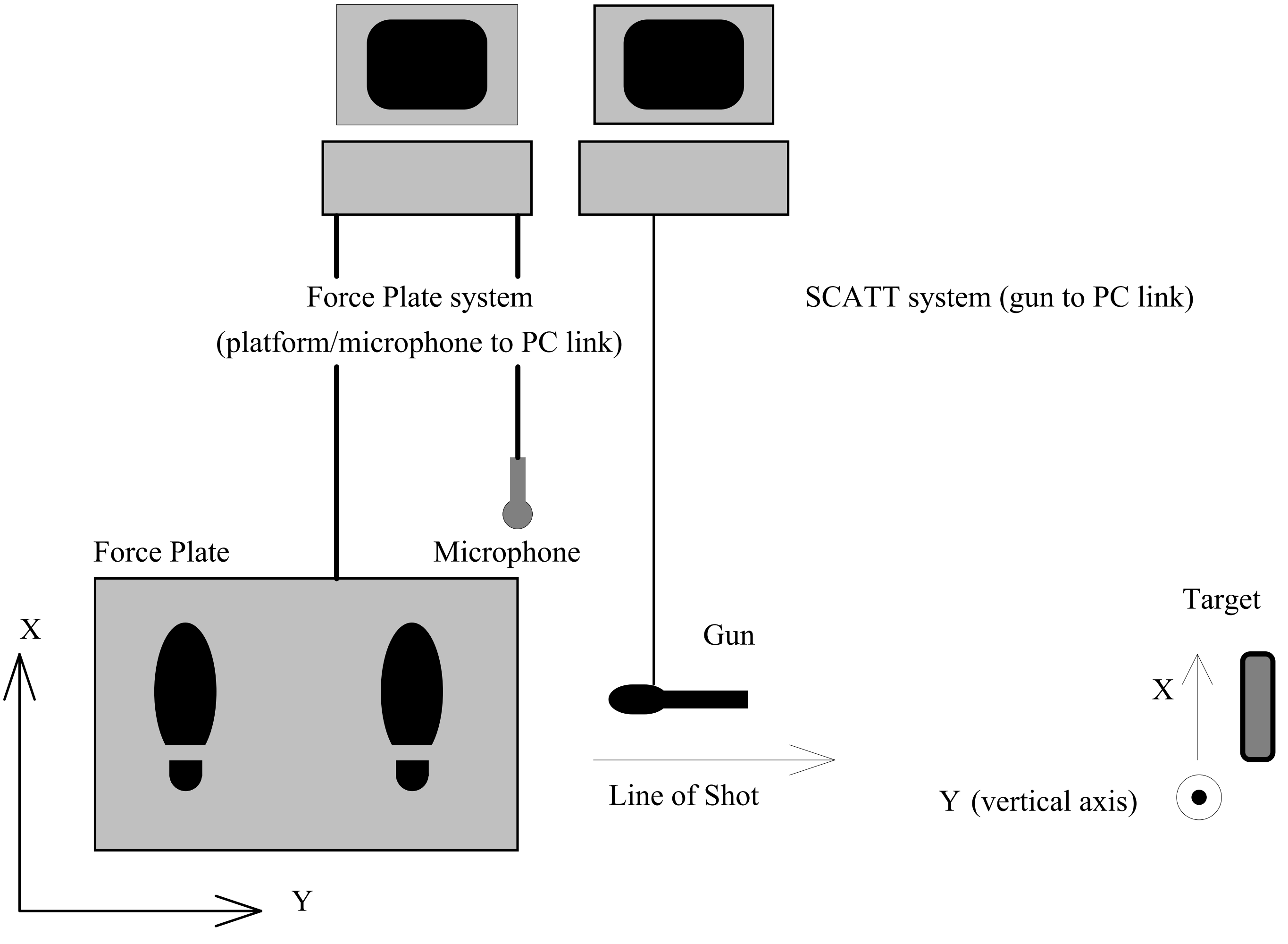


Figure 4.2.1: Laboratory set-up (force plate and SCATT systems) for testing.

In all aspects of task and laboratory set-up, rules and conditions of shooting, as per "Official statutes, rules and regulations" set out by the International Shooting Union (1996) were adhered to.

4.2.4 Shooting Performance

Shooting performance was measured by three variables, as detailed in Table 4.2.2. These were obtained from the SCATT system, detailed in section 4.2.6. The result of each shot was made available to each shooter as allowed in competition.

Table 4.2.2: Performance measures of shooting used in this study

Parameter	*Description*
Result	Score of shot to 1 decimal place (maximum 10.9)
PosX	Horizontal displacement of shot from target centre (mm)
PosY	Vertical displacement of shot from target centre (mm)

Absolute values were obtained for PosX and PosY to allow for the calculation of a mean error in the X and y-axis. No analysis of the direction of this error (above or below, right or left of target centre) was performed.

Total aim time, defined as the time from the first instant the aim point of the gun was on the target to the point of shot, was also quantified.

Each set of 20 shots was averaged to obtain a mean value for each shooter for that parameter. These mean values were then used to obtain group means.

4.2.5 Body Sway Measurement

An AMTI LG6-4 force plate (1200mm x 600mm) was located directly below the shooting area. Shooters stood in their preferred shooting position on the plate. During testing, the researcher ensured the shooter was, at all times, wholly on the force plate. The force plate axes were oriented such that the y-axis was parallel to the line of shot and the x-axis was oriented in the same horizontal plane and perpendicular to the line of shot.

Force and moment data were passed through an AMTI SGA6-4 amplifier set at its maximum gain of 4000 and with the signal passing through a 10.5Hz low pass filter in-built in the amplifier. A sensitive microphone was located unobtrusively near the shooting area to detect the sound of the shot. The sound signal was processed by a Peak Performance Technologies (PEAK) Event Synchronisation Unit (ESU) and passed to a connector box to be incorporated with the six force plate channels. The trigger was used to synchronise force plate data to the point of shot and to allow for synchronisation of force plate and SCATT (aim point) data.

After the force plate signal was amplified, the six force plate channels and trigger channel were passed to an AMLAB 16-bit data acquisition system. Data was acquired for the 5.0s immediately before shot, with the microphone trigger controlling timing of data collection. Data was sampled at 128Hz, to coincide with the sample time and rate of the aim point measurement system.

On completion of data collection, data were transferred to Microsoft EXCEL for analysis. Data was smoothed using a fourth order Butterworth digital filter (as detailed by Winter, 1990) with a cut off frequency of 4Hz and Force, COP and Tz data were calculated (as per table 4.2.3) using the smoothed data. The process of deciding on this smoothing cut off frequency is summarised in methods section 4.2.10, with complete results and discussion in Appendix D. Each set of 20 shots was averaged to obtain a mean value for each shooter for that parameter. These mean values were then used to obtain group means.

Table 4.2.3 and figure 4.2.2 summarises the parameters quantified for the assessment of body sway.

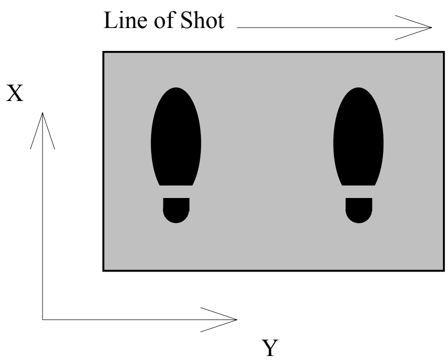
Table 4.2.3: Parameters used in body sway assessment

Parameter	*Definition*
FxRange	Force range in x-axis
FxSD	Standard deviation of signal in Fx
FyRange	Force range in y-axis
FySD	Standard deviation of signal in Fy
COPxLength	Total distance the COP moves in the x-axis
COPxRange	Distance between maximum and minimum COPx location
COPxSD	Standard deviation of the COPx position
COPyLength	Total distance the COP moves in the y-axis
COPyRange	Distance between maximum and minimum COPy location
COPySD	Standard deviation of the COPy position
COPAbsLength	Total distance the COP moves (in horizontal plane)
COPAbsRange	Sum of COPxRange and COPyRange
COPxVelSD	Standard deviation of COP velocity in the x-axis
COPyVelSD	Standard deviation of COP velocity in the y-axis
COPAbsSpeedAve	Average COP speed in the horizontal plane
COPAbsSpeedSD	Standard deviation of COP speed in the horizontal plane
TzRange	Range of Torque about the Z axis passing through the COP
At Shot	
COPxSpeed	
COPySpeed	
COPAbsSpeed	
Tz	

Ave = average
Abs = absolute
SD = standard deviation

Parameter

COP Axes



COPx, COPy, COPAbs Length

COPx, COPy, COPAbs Range

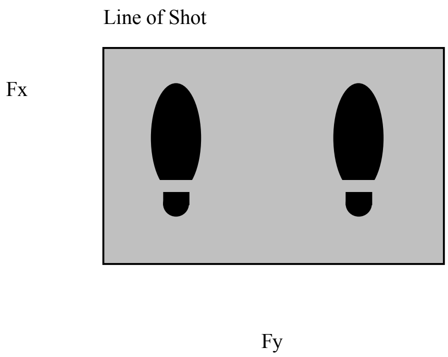
COPxSD, COPySD

COPxVelSD, COPyVelSD,

COPAbsSpeedSD

COPAbsSpeedAve

Force (Fx, Fy)



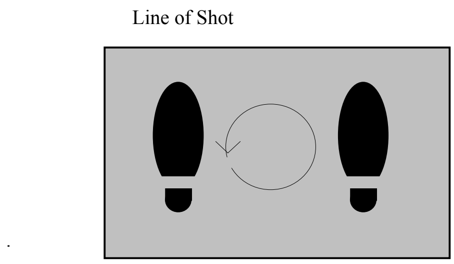
FxRange

FxSD

FyRange

FySD

Torque (Tz)



Tz Range

Figure 4.2.2: Measurement set-up for parameters assessing body sway.

The number of body sway parameters was initially kept large to gain greater insight into which values may be useful in the assessment of body sway in shooting. The number of parameters were cut down after examination of data (refer to results section 5.2.1.3)

The initial choice of parameters was based on previous shooting and body sway research. All COP measures have been used previously in shooting and postural assessment research. Fx and Fy deviation were included based on the findings of Goldie *et al.* (1989) that the variability of the force in the X and Y axes was a more reliable and better differentiating measure of sway than were COP measures.

Tz has not been used previously in shooting or posture research. The inclusion of Tz is based on the observation by the researcher that small rotations which will generate torque about the Z axis could produce horizontal aim point fluctuations. This movement could be associated with moving the gun horizontally across the target for aim point adjustment. Movement of shooters, if rotational about a vertical axis, would not be detected by COP measurement.

After smoothing the raw data, COP was calculated using the COP equations provided with the AMTI software manual (detailed in the next section). COP velocities were calculated from this data using a three point central differences method, presented below (Nakamura, 1993).

$$f_i' = \frac{f_{i+1} - f_{i-1}}{2h}$$

Where i = current point

h = time interval between force plate samples (1/128s for this study)

All parameters were calculated for the time periods of 5s, 3s and 1s prior to shot. This was to align with the output available from the aim point data.

4.2.6 Aim Point Fluctuation

Aim point fluctuation was measured using a SCATT Shooting Training and Analysis System (version 1.1). The system included an instrumented target holder, receiver (attached to the barrel of the gun and cabled to the serial port of a PC) and software which collected and stored XY co-ordinates of the aim point on the target (figure 4.2.3). The target holder contained four point sources of infra red emission; one housed in the middle of each upright (2) and crossbeam (2) of the frame. These infrared beams were detected by the receiver and focused, using a lens, on a back-plate, where they were encoded. The location of the focused infrared beam corresponds to the aim point of the gun on the target. The signal was passed to a 486/33 PC (separate from the force plate PC) where the SCATT software recorded the XY co-ordinates of the aim point from the time the aim point was first on the target until 0.5s after the shot was fired. The receiver detected the point of shot by sensing the sudden vibration produced by the gun when fired. The manufacturers nominally quote the accuracy of this system as ±0.1mm.

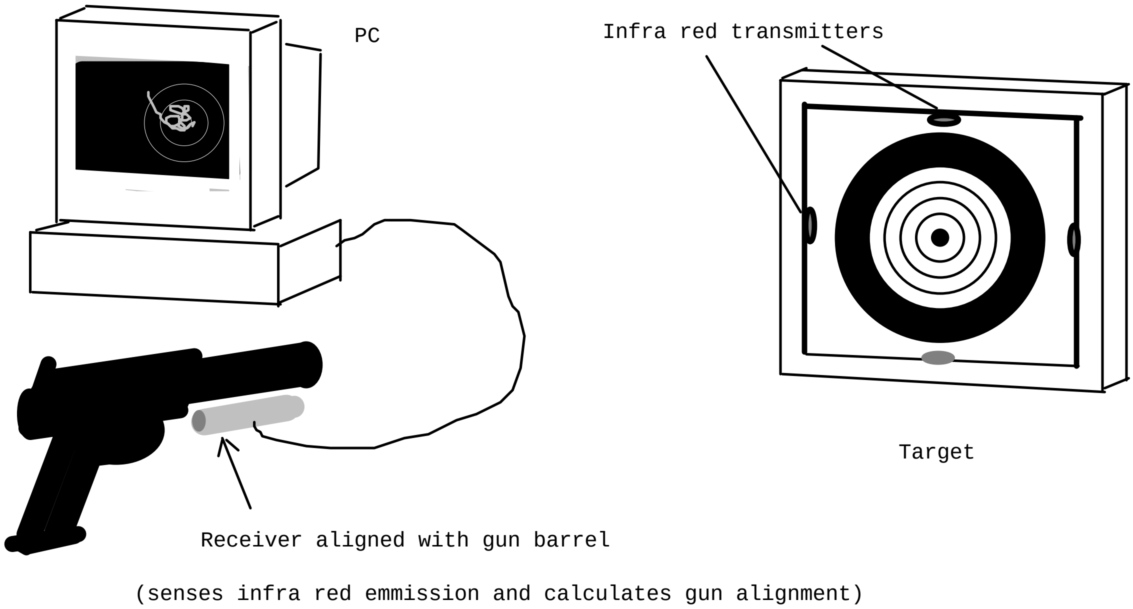


Figure 4.2.3: SCATT testing set-up, with instrumented target, receiver attached to the gun and connection to SCATT software

SCATT software was set up to output the XY aim point trace and position of shot on the computer screen, as shown in figure 4.2.4. The x-axis of the SCATT system was aligned horizontally and the y-axis vertically on the target.

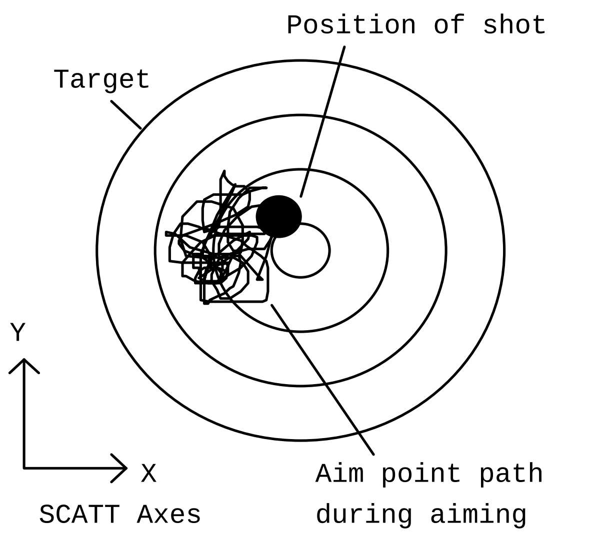


Figure 4.2.4: SCATT system output.

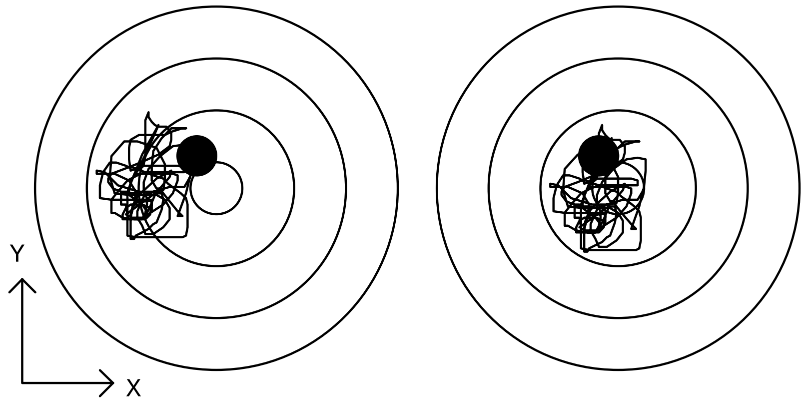
Initially, the raw XY co-ordinates from the SCATT data were to be converted to text and transferred to EXCEL, where further analysis of aim point fluctuation was to be performed. However, difficulties with obtaining appropriate software and file formats from the manufacturers to accomplish this task forced this analysis to be eliminated from the study. Hence, aim point parameters were limited to those output by the SCATT software. Table 4.2.4 details the SCATT-based parameters. As for body sway data, each set of 20 shots was averaged to obtain a mean value for each shooter for that parameter. These mean values were then used to obtain group means.

Table 4.2.4: Parameters calculated using SCATT software

Parameter	*Definition*
Std10.0	% time the aim point spends in the 10 scoring zone
Std10a0	% time the aim point spends in an area the size of the 10 scoring zone
Length	Length of aim point trace
LengthX	Length of aim point trace in the X (horizontal) axis
LengthY	Length of aim point trace in the Y (vertical) axis

Note Std = Relative aim point steadiness

The Std parameters in table 4.2.4 refer to the relative steadiness or the percentage time spent by the aim point in a certain area relative to the total measurement time (ie. 5s, 3s, 1s prior to shot). The SCATT (1991) manual defines Std10.0 as a measure of aim point accuracy and Std10a0 as a measure of the quality of the aim point hold. As such, they provide an overall measure of steadiness of the aim point (see figure 4.2.5). The '10.0' area refers to the zone in which a '10' can be scored. The Std10a0 parameter refers to the same zone size, but is independent of location of this zone on the target. Rather the maximum % time spent in this zone is calculated, regardless of position on target. A shooter may exhibit an extremely stable aim point but does not align the aim point on the centre of the target. This parameter assesses the steadiness of the hold only, with no reference to the target centre.



(i) Std10a.0 = 50%
Std10.0 = 0%

(ii) Std10a0 = 50%
Std10.0 = 50%

Figure 4.2.5: SCATT Std10.0 and Std10a0 measures.

Figure 4.2.5 shows two similar aim point patterns. Figure 4.2.5 (ii) is centred about the target centre, while figure 4.2.5 (i) is centred to the left of the target centre. The use of the steadiness in an area equivalent to the 10 ring is clearly of use in this instance. The shooter is making a systematic error in aiming in figure 4.2.5 (i), but is exhibiting an equivalent steadiness to that exhibited in figure 4.2.5 (ii).

4.2.7 ECG and breathing data

ECG and breathing data were also monitored during testing.

After appropriate skin preparation, three ECG electrodes (Medi-Trace Mini, Graphic Controls Corp) were placed on the chest (sternum, right and left side of chest at approximately the level of the 10th rib). A ‘rubbery ruler’ (described as a wide range, comfortable capacitive displacement transducer, developed by The University of Melbourne School of Physics), consisting of a strip of inextensible velcro attached to each end of a flexible cable, was used to monitor breathing. This was wrapped around the chest of each shooter, such that the cable and velcro formed a “chest belt”. As the chest expanded and contracted during breathing, the cable would stretch and shrink proportionally. The resultant output of the rubbery ruler was a signal that corresponded to the expansion and contraction of the chest during breathing.

Both sets of data (ECG and rubbery ruler) were passed to an AMLAB data acquisition system and processed using AMLAB software configured for the task. Heart rate, in beats per minute, was calculated from the ECG trace. The ECG trace, heart rate and breathing trace were displayed in real time on the computer monitor, and fed to a Vinegen VGA to PAL converter to be combined with live video data of the shooter. The data was not stored on the computer. No further analysis was performed on this data for this thesis, although the coaches used it.

4.2.8 Video

A PAL video camera (Panasonic wv-CL350) was located approximately 4 metres from the shooting area, and was aligned such that the angle of view was perpendicular to the line of shot during testing. This signal was fed first into the PEAK Event Synchronisation Unit to insert a small white square on the video when a trigger was detected from the microphone. The video then passed to a PEAK Time Synchronisation Unit which overlaid a time clock, running continuously, on the video.

The signal was then passed to a Vinegen (MLP-001515) VGA to PAL converter, where it was combined with ECG and breathing data from the AMLAB PC. A video mixer (Videotronics Digital Video Mixer, MX-1P) was used to combine this video signal with SCATT output data from the Averkey3 VGA-PAL converter. The mixer output was recorded using a Panasonic SVHS NV-FS90 PAL VCR. Figure 4.2.6 shows an example of the video image recorded during testing, and figure 4.2.7 shows the full equipment configuration.

Video was recorded to be used as feedback for the shooters and coaches after the study, as well as provide a means to check any inappropriate triggering of the force plate system or testing problems.

Figure 4.2.6: Example output of video overlay system.

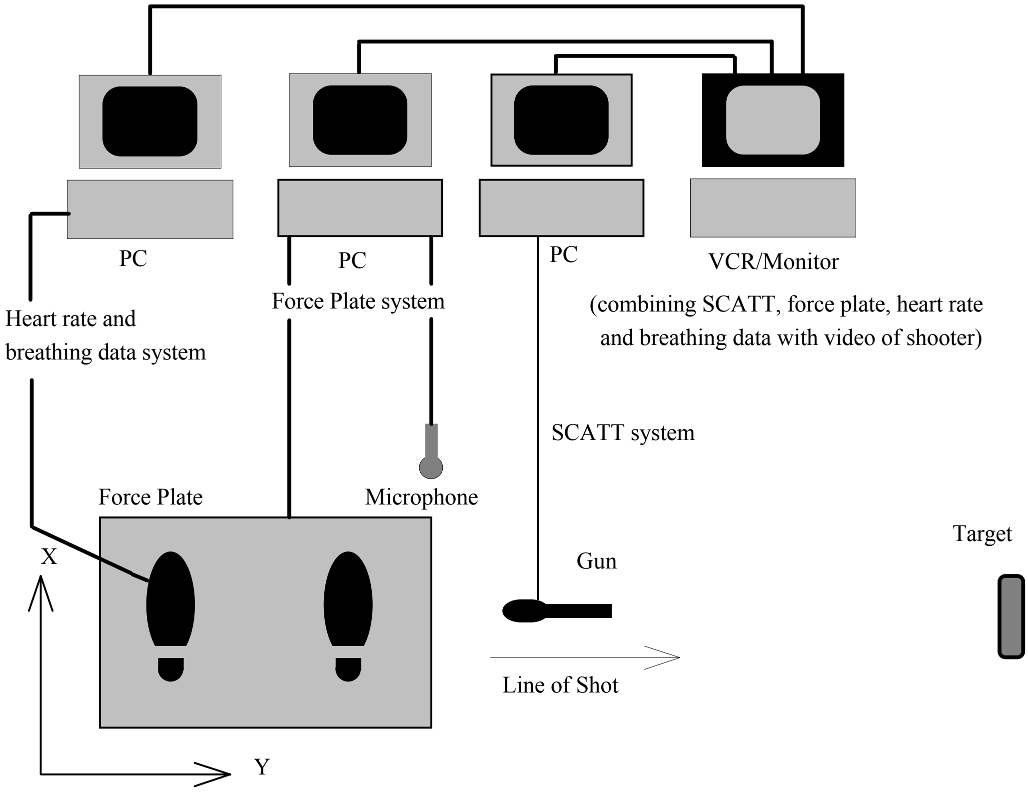


Figure 4.2.7: Complete equipment configuration for testing.

4.2.9 Statistical Analysis

4.2.9.1 Reduction of Body Sway Parameters

After body sway parameters for each individual had been quantified and individual and group means calculated, parameters were examined to establish how many were required to adequately describe body sway in this study. This was performed using a combination of Principal Components Analysis (PCA), cross correlations and theoretical analysis. This process is detailed fully in section 5.2.1.

4.2.9.2 Body Sway, Aim point and Shooting Performance

Pearson's correlations were performed on mean parameter values for the groups as well as each individual. As will be discussed in section 5.2.3, the pistol shooting group and individual analysis was limited to the 1s period only:

- Body sway parameters measured over 5s, and shooting performance
- Body sway parameters measured over 3s, and shooting performance
- Body sway parameters measured over 1s, and shooting performance
- Aim point parameters measured over 5s, and shooting performance
- Aim point parameters measured over 3s, and shooting performance
- Aim point parameters measured over 1s, and shooting performance
- Body sway and aim point parameters measured over 5s
- Body sway and aim point parameters measured over 3s
- Body sway and aim point parameters measured over 1s

The scattergraph for each correlation was examined using z scores of each parameter. Z scores were calculated for the mean parameter value for each shooter, relative to the group mean in the case of the group analysis, and the z score of each shot relative to the individual's mean, in the case of the individual shooter analysis. A two-tailed significance level (p value) was also obtained for appropriate correlations. Initially, it was thought that some relationships would be directional and a one tailed test may be appropriate. However, as this work was largely exploratory in nature and no clear direction of these relationships was indicated in the literature, it was considered more appropriate to use a two tailed test as the direction of the relationship could not realistically be predicted.

On completion of this correlation analysis, it was considered necessary to examine the collective effect of body sway parameters on performance, of aim point parameters on performance and of body sway parameters on aim point parameters. As such, multiple regression analysis was performed on individual shooter data. Due to low subject numbers, this analysis was not performed on the group data. Multiple regression analysis was performed using a combination of Cv and Best Multiple R^2 assessment, as recommended by Daniel and Wood (1980). Cv refers to the total square error of the regression. Daniel and Wood (1980) refer to this error as 'Cp', with 'p' used to denote the number of variables used in the Cp analysis. Since 'p' has been used in this study to denote the alpha, or significance, level for statistical analyses, 'Cv' and 'v' have been used to avoid confusion. The Best Multiple R^2 technique involves calculating the R^2 value for all possible combinations of independent variables to find the largest value. A best subsets analysis was performed on body sway data and performance, aim point data and performance, and body sway and aim point data using Minitab 12 statistical software. Cv was then graphed against v (number of variables) for each subset analysis. The number of variables (and the variables themselves) chosen for entry into the multiple regression was an ad hoc combination of the largest R^2 value for the smallest Cv (error) value. This is explained in more detail in section 5.2.2.2.

The selection of significance (p) levels is somewhat contentious in the literature. While 0.05 is an accepted value to use, Winer (1971) suggested that the selection of a p value of 0.05 was based merely on convention, rather than considered decision. Winer suggested values up to $p=0.2$ and $p=0.3$ may be more appropriate where statistical power is low. Franks and Schuyler (1986) also recommended that less rigorous levels of p should be selected for studies with limited power. Further, Franks and Schuyler recommend that p values be reported for all relationships, so as to enable the reader to make decisions at different levels for the reported relationships, rather than relying on the authors decision.

Based on this literature, the level of significance for correlation and multiple regression analysis was nominally set at $p<0.05$ and $p<0.01$ to provide information consistent with that existing in the majority of biomechanics literature. However, discussion was not limited to relationships meeting this p value criterion only. Rather, statistical analyses between body sway, aim point fluctuation and performance with higher p values than 0.05 have also been discussed in terms of being potentially significant in this study, with both correlation coefficient (r value) and p values being reported in these instances.

4.2.10 Smoothing

To decide on an appropriate smoothing cut-off frequency, spectral and residual analyses were performed. Spectral analysis was conducted on raw force plate data (F_x, F_y, F_z, M_x, M_y, M_z) as well as COP data calculated from this raw data to examine the predominant frequencies that exist in each signal. Residual analysis was performed on raw and smoothed force plate data to examine the effects of different smoothing cut-off frequencies on the individual force channels. For this purpose, one rifle-shooting trial from each of four shooters (two pistol and two rifle shooters) was chosen at random. One set of data is presented in full in Appendix D. All analyses showed reasonably consistent results between shooters.

Prior to spectral analyses, data (5s, or 640 data points) was detrended and zero padded to make 1024 data points. Spectral analysis was then performed by first analysing the detrended and zero padded raw data using the Fourier function in Microsoft EXCEL, which was then parsed using a custom written macro to obtain a frequency spectrum. This analysis was conducted on the raw force and moment data (Fx, Fy, Fz, Mx, My, Mz) of the randomly selected rifle shooter's trial as well as COP data calculated from this raw data. Also, one data set was obtained by ensemble averaging body sway data from ten trials from this rifle shooter prior to detrending and zero padding. This served to eliminate random noise and gain an insight into the predominant frequencies in the signal. This averaging was initially conducted on the raw force and moment data after which spectral analysis was performed. However, as synchronisation of the signals lay only with the point of shot, some sway phase differences existed, which tended to reduce or cancel some of the frequency amplitudes that were thought to be due to sway. As such, the spectral analyses from the ten individual trials were ensemble averaged and used for analysis. Used in conjunction with the spectral analyses of the single trials and residual analyses, this procedure served to build a framework to establish appropriate cut-off frequencies for smoothing. The analysis for one shooter is also presented in Appendix D.

Residual analysis was conducted on force and moment channels using the methods outlined by Winter (1990). Each force plate channel was smoothed at cut-off frequencies ranging from 2Hz to 10Hz, using a 4th order Butterworth digital filter (also described in Winter, 1990) and the residual was calculated for each channel. The residual of function (f_c) is presented below.

$$R(f_c) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{ir} - x_{is})^2}$$

Where x_{ir} = raw data at the *i*th sample

x_{is} = smoothed data at the *i*th sample

Based on these analyses, a cut-off frequency of 4Hz was decided upon for all channels. Remembering that the nature of the recursive filter will effectively reduce this cut-off to 3.2Hz, the decision of 4Hz was based on the compromise between leaving the COP frequency below 3Hz unchanged, while eliminating as much of the 4Hz BCG signal as possible. Some signal below 3Hz signal will be reduced and some 4Hz signal will pass through the filter, but, as noted by Winter (1990), smoothing is always a trade off between eliminating signal and allowing noise to pass through the smoothing process. Visual inspection of force and COP curves indicated that this smoothing cut-off was appropriate.

CHAPTER 5 RESULTS

5.1 STAGE 1

5.1.1 Quantisation

The next section analyses the error in measurement propagated from output AMTI and Kistler force plates commonly used in stability assessment. Proofs for 12-bit ADC data collection from the AMTI LG6-4 plate, used in this study, and the Kistler 9287A plate have been presented. Proofs for the same force plates using 16-bit ADC data collection have been included in Appendix A.

It should be noted that error and resolution analyses have been limited to issues of quantisation only. Also, these calculations are based on raw data. Appropriate smoothing will reduce these errors and generate a value that is closer to the true value.

5.1.1.1 Propagation of uncertainty due to quantisation error in COP calculations (AMTI LG6-4 and KISTLER 9287A)

The centre of pressure of forces acting on a force plate is calculated using the following formulas (measures shown graphically in figure 5.1.1.1):

$$COPx = \frac{-My + (Fx * Dz)}{Fz} \qquad \text{eqn 5.1}$$

$$COPy = \frac{Mx + (Fy * Dz)}{Fz} \qquad \text{eqn 5.2}$$

where COPx = location of the COP in the x-axis (m)
COPy = location of the COP in the y-axis (m)
Mx = moment about the force plate x-axis (Nm)
My = moment about the force plate y-axis (Nm)
Fx = force in x-axis (N)
Fy = force in y-axis (N)
Fz = force in z-axis (N)
Dz = height of top of plate above the measurement (XY) plane (m)

NB Dz is manufacturer specified and assumed constant for this analysis

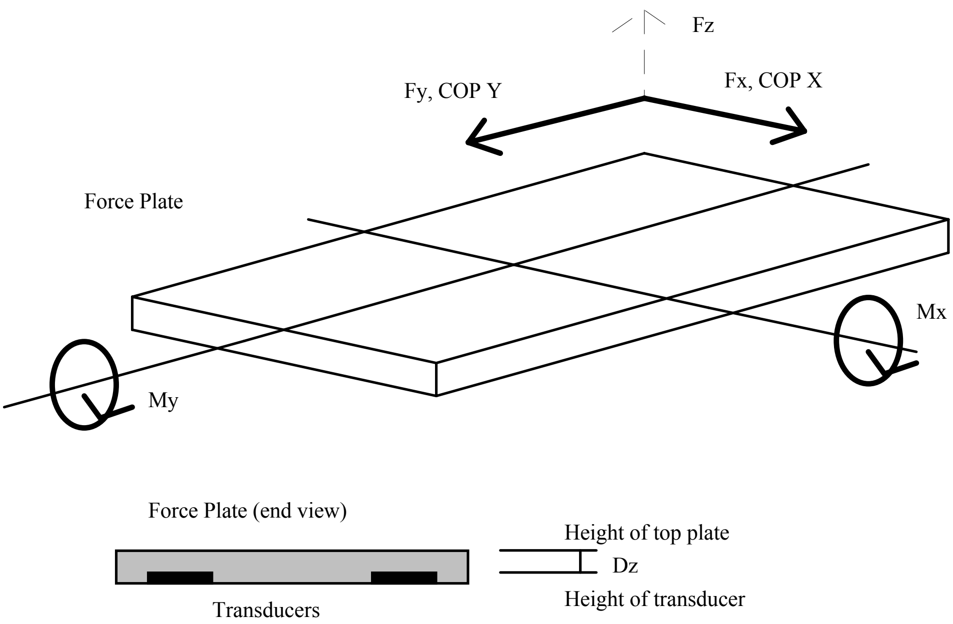


Figure 5.1.1.1: Force plate axes for force and moment measurement and Dz value.

AMTI force plates output six channels of data, three force channels (Fx, Fy, Fz) and three moment channels (Mx, My, Mz). Kistler force plates output eight channels of force data; four Fz, two Fx and two Fy channels. Moments and sums of forces are calculated from these channels before moving on to the COP equations (eqn 5.1 and eqn 5.2).

5.1.1.1.1 AMTI LG6-4 Force Plate

5.1.1.1.1.1 Propagation of quantisation error in a single measure of COP using 12-bit ADC

The error calculation below is for the measurement of a single COP value. The error values calculated correspond to the maximum error that can be produced by quantisation during measurement. Results have not been rounded until the final result.

Type AMTI LG6-4
12-bit ADC
Gain: 4000 (maximum setting on AMTI SGA6-4 amplifiers)
Dimensions: 610mm X 1220mm

Table 5.1.1.1 shows values used in error approximations. Quantisation steps are the increments or smallest units in which each channel is measured for the AMTI LG6-4 force plate as the signal is converted from analogue to digital. These values are based on transducer sensitivities, amplifier gain settings and 12-bit ADC. Measurement error due to quantisation (quantisation error) is half this value (eg a quantisation step of 0.37N can be measured to a precision of ± 0.185N). The measured values are taken from a randomly selected pistol shooting trial completed during testing and are typical of values obtained for other trials. Error is denoted by the symbol (δ).

Table 5.1.1.1: Quantisation step *, error and example values for AMTI LG6-4 force plate

	Minimum quantisation step (N / Nm)	Quantisation error (± N, ± Nm)	Measured values (N / Nm)
Fx	**0.37**	**± 0.185**	**2**
Fy	**0.37**	**± 0.185**	**1**
Fz	**1.42**	**± 0.71**	**750**
Mx	**0.34**	**± 0.17**	**24**
My	**0.24**	**± 0.12**	**55**

* Minimum quantisation step refers to the smallest quantisation step or unit for each channel as provided by the ADC system.

Uncertainty for COPx:

*(referring to eqn 5.1) Let (Fx * Dz) = A*

The value of A, using the values from Table 5.1.1.1 is:

$$A = Fx * Dz$$

$$A = 2 * -0.0535$$

$$A = -0.428 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fx| * Dz$$

$$|\delta A| \leq 0.185 * 0.0535$$

$$|\delta A| \leq 0.0099 \text{ Nm}$$

Whilst the relative error of Fx is quite large (0.185N), its significance in COP calculations is small.

*(referring to eqn 5.1) Let - My + (Fx * Dz) = B*

The value of B, using the values from Table 5.1.1.1 is:

$$B = - My + A$$

$$B = - 55 + -0.428$$

$$B = - 55.428 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta My| + |\delta A|$$

$$|\delta B| \leq 0.12 + 0.0099$$

$$|\delta B| \leq 0.1299 \text{ Nm}$$

Note that the error due to My is far larger than the error due to Fx (My accounts for approximately 92% of error in the numerator of the COP calculation).

Recalling eqn 5.1

$$COPx = \frac{-My + (Fx * Dz)}{Fz}$$

The value of COPx, using the values from Table 5.1.1.1:

From previous definition, - *My + (Fx * Dz) = B*

$$COPx = \frac{B}{Fz}$$

$$COPx = \frac{-55.428}{750}$$

$$COPx = -0.07348m$$

Error associated with COPx:

$$\left|\frac{\delta COPx}{COPx}\right| \leq \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

From Table 5.1.1.1 δFz = 0.71N and Fz = 750N

$$\left|\frac{\delta COPx}{COPx}\right| \leq \left|\frac{0.1299}{-55.428}\right| + \left|\frac{0.71}{750}\right|$$

$$\left|\frac{\delta COPx}{COPx}\right| \leq 0.236\% + 0.095\% \leq 0.331\%$$

So there is an error of approximately 0.3% in COPx calculations due to quantisation error for the given values of force and moment data.

Thus

$$\text{COPx} = -0.07348\text{m} \pm 0.000243\text{m}$$

or

$$\boxed{\text{COPx} = -73.5\text{ mm} \pm 0.2\text{mm}}$$

While the error here is low relative to the absolute value, it is large relative to measures that have been reported in shooting research of between 1mm and 4mm. This is discussed in section 5.1.6.3.

Uncertainty for COPy

*(referring to eqn 5.2) Let (Fy * Dz) = A*

The value of A, using the values from Table 5.1.1.1 is:

$$A = Fy * Dz$$
$$A = 1 * -0.0535$$
$$A = -0.0535 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fy| * Dz$$
$$|\delta A| \leq 0.185 * 0.0535$$
$$|\delta A| \leq 0.0099 \text{ Nm}$$

Whilst the relative error of Fy is quite large (0.185N), its significance in COP calculations is small

*(referring to eqn 5.2) Let Mx + (Fy * Dz) = B*

The value of B, using the values from Table 5.1.1.1 is:

$$B = Mx + A$$
$$B = 24 \text{ Nm} + -0.0535$$
$$B = 23.9465 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta Mx| + |\delta A|$$
$$|\delta B| \leq 0.17 + 0.0099$$
$$|\delta B| \leq 0.1799 \text{ Nm}$$

Note that the error due to Mx is far larger than the error due to Fy (Mx accounts for approximately 94% of error in the numerator of the COP calculation).

Recalling eqn 5.2

$$COPy = \frac{Mx + (Fy * Dz)}{Fz}$$

The value of COPy, using the values from Table 5.1.1.1:

From previous definition, *Mx + (Fy * Dz) = B*

$$COPy = \frac{B}{Fz}$$

$$COPy = \frac{24.0535}{750}$$

$$COPy = 0.03207m$$

Error associated with COPy:

$$\left|\frac{\delta COPy}{COPy}\right| \le \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

From Table 5.1.1.1, δFz = 0.71 and Fz = 750N

$$\left|\frac{\delta COPy}{COPy}\right| \le \left|\frac{0.1799}{24.0535}\right| + \left|\frac{0.71}{750}\right|$$

$$\left|\frac{\delta COPy}{COPy}\right| \le 0.748\% + 0.095\% \le 0.843\%$$

So there is an uncertainty of approximately 1% in COPy calculations due to quantisation error for the given values of force and moment data.

Thus

$$\text{COPy} = 0.03207\text{m} \pm 0.000270\text{m}$$

or

$$\boxed{\text{COPy} = 32.1 \text{ mm} \pm 0.3\text{mm}}$$

Based on this calculation, a 750N shooter's COP at this particular instant of measurement is located at x-y co-ordinates (-73.5 ± 0.2mm, 32.1 ± 0.3mm). COP error owing to quantisation of 0.2mm in the x-axis and 0.3 mm in the y-axis exists in this measure. The significance of this will, of course, depend on the required COP precision required to gain meaningful information. As for the error in COPx, this error is low relative to the absolute value of COPy but high relative to shooting sway values. This is discussed in section 5.1.6.3.

5.1.1.1.1.2 Propagation of quantisation error with changing COP values using 12-bit ADC

To examine how the error in COP measurement due to quantisation changes as conditions (ie force and moment values) change, error approximations were calculated for a range of force and moment values. The lower values of Mx and My (0Nm and 100Nm) were encountered in this study and would be likely to exist in most force plate data measuring body sway of shooters, as the shooter will usually be positioned about the centre of the plate.

Table 5.1.1.2 reports the error in COP measurement due to quantisation for a range of Fz, Mx and My values (calculated using the same procedures as above). Error values have been reported to 3 decimal places for comparison purposes. This level of accuracy will be unachievable using 12-bit ADC.

Table 5.1.1.2: Quantisation error in COP calculations for a range of Fz, Mx and My values for the AMTI LG6-4 force plate (Fx, Fy = 1N)

	My 0Nm	Mx 0Nm	My 100Nm	Mx 100Nm	Maximum My (val in brackets, Nm)	Maximum Mx (val in brackets, Nm)
Fz (N)	± COPx mm	± COPy mm	± COPx mm	± COPy mm	± COPx mm	± COPy mm
500	**0.260**	**0.360**	**0.544**	**0.644**	**0.692 (152)**	**1.223 (304)**
600	**0.217**	**0.300**	**0.414**	**0.497**	**0.576 (182)**	**0.020 (365)**
700	**0.186**	**0.257**	**0.331**	**0.402**	**0.494 (213)**	**0.874 (426)**
800	**0.162**	**0.225**	**0.273**	**0.336**	**0.432 (243)**	**0.765 (487)**
900	**0.144**	**0.200**	**0.232**	**0.288**	**0.357 (274)**	**0.680 (548)**
1000	**0.130**	**0.180**	**0.201**	**0.251**	**0.346 (304)**	**0.612 (609)**
1100	**0.118**	**0.164**	**0.177**	**0.222**	**0.315 (335)**	**0.557 (670)**

Maximum moment values correspond to a person standing on the edge of the force plate.

As can be noted in Table 5.1.1.2, as Fz increases, the absolute error due to quantisation decreases for any moment value for both COPx and COPy. As Fz increases, the partial derivative of Fz is decreased. Hence the relative error due to Fz is decreased. Wisleder and McLean (1991) report similar findings in experimental data, with COP fluctuation, as measured by COP displacement range and standard deviation, of a stationary weight placed on the force plate decreasing as Fz increased. Based on this result, lighter shooters will produce data that is potentially more inaccurate, due to the larger error due to quantisation at lower Fz values. This effect is presented graphically in figures 5.1.1.1.2 and 5.1.1.1.3. Each curve corresponds to quantisation error in COP using different moment values.

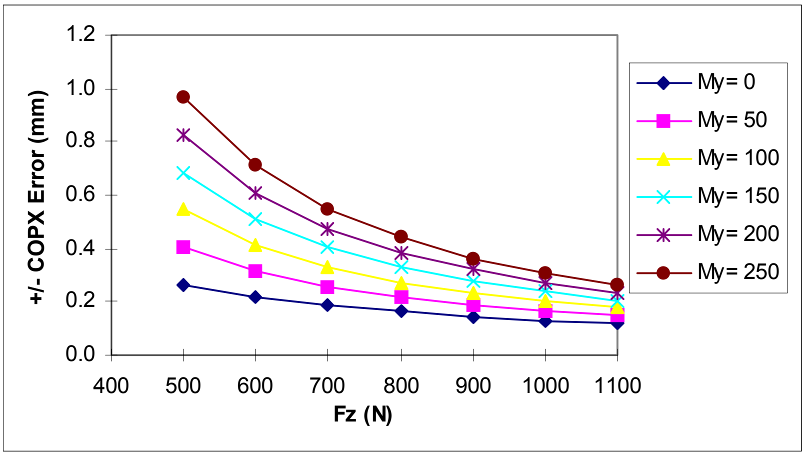


Figure 5.1.1.2: Relationship between increasing values of My and Fz on quantisation error in COPx calculations for the AMTI LG6-4 (All My values in Nm, Fx =1N).

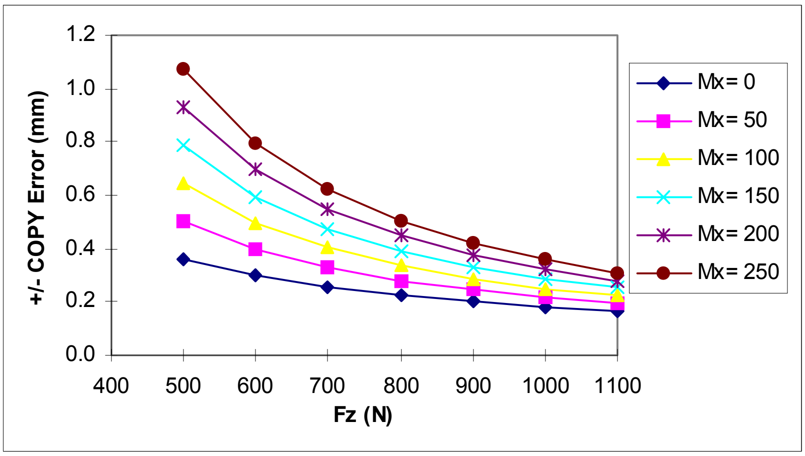


Figure 5.1.1.3: Relationship between increasing values of Mx and Fz on quantisation error in COPy calculations for the AMTI LG6-4 (All Mx values in Nm, Fy=1N).

It can also be noted from figures 5.1.1.2 and 5.1.1.3, as moment values increase, errors increase (for the same Fz value). This is indicated by the degree of separation of each curve. This is due to an increase in the relative influence of the error in the numerator of the COP equation (as per eqn 5.1 and eqn 5.2). The average values for Mx and My taken from a sample of four shooters (two rifle, two pistol) were approximately 50Nm, with the maximum moment recorded as 95Nm. Moment values would be unlikely to exceed this value as a two footed stance with the feet a reasonable distance apart (as is usually the case in the shooting position) will generate COP positions about the centre of the plate. As such, errors between 0.2mm and 0.5mm might be expected for single measures of COP in shooting. Maximum error due to Mx and My will occur at the maximum values of Mx and My, although these values would never be encountered in a shooting analysis and have been reported only to show the upper limit of error due to quantisation in force plate measurement. The larger error values in the COP calculations with larger Mx and My indicate that more accurate data for a single measure of COP will be obtained if the subject is located closer to the centre of the plate, reducing the magnitude of the moment.

COP error values with changing force (Fx and Fy) values are reported in table 5.1.1.3. The change in quantisation error in COP for Fx and Fy values between 0N and 100N is very small, with a maximum increase in error of 0.015mm for Fz = 500N and as little as 0.003mm for Fz = 1100N. The increase in error across the full range of Fx and Fy values was less than 0.12mm. The maximum Fx and Fy value found in the body sway data of four shooters tested in this study was approximately 3N. Given that Fx and Fy will fluctuate about zero, the horizontal force plane values will probably never exceed 10N. The influence, then, of Fx and Fy to errors in calculation of COP during shooting will be negligible.

Table 5.1.1.3: Quantisation error in COP calculations for a range of Fz, Fx and Fy values for the AMTI LG6-4 force plate (Mx, My = 1Nm)

	Fx=0N	Fy=0N	Fx=100Nm	Fy=100N	Maximum Fx (755N)	Maximum Fy (753N)
Fz (N)	± COPx mm	± COPy mm	± COPx mm	± COPy mm	± COPx mm	± COPy mm
500	**0.263**	**0.363**	**0.278**	**0.378**	**0.377**	**0.477**
600	**0.218**	**0.302**	**0.229**	**0.312**	**0.298**	**0.381**
700	**0.187**	**0.258**	**0.195**	**0.266**	**0.246**	**0.317**
800	**0.163**	**0.226**	**0.169**	**0.232**	**0.208**	**0.271**
900	**0.145**	**0.201**	**0.150**	**0.205**	**0.181**	**0.236**
1000	**0.131**	**0.181**	**0.134**	**0.184**	**0.159**	**0.209**
1100	**0.119**	**0.164**	**0.122**	**0.167**	**0.142**	**0.188**

Figures 5.1.1.1.4 and 5.1.1.1.5 show the effects of increased Fx and Fy values on COP error for different Fz values. As Fz (on the x-axis) increases from left to right, the error decreases for the same Fx and Fy values. However, the lack of separation between each curve in these figures represents the minimal effect of change in Fx and Fy on COP error due to quantisation.

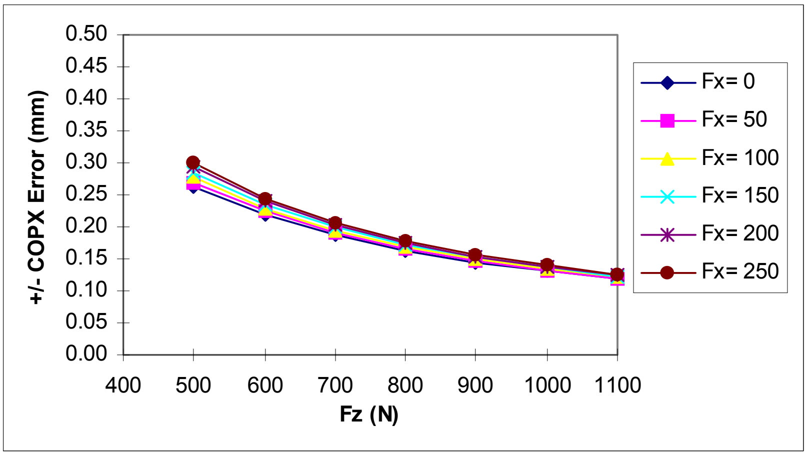


Figure 5.1.1.1.4: Relationship between increasing values of Fx and Fz on quantisation error in COPx calculations for the AMTI LG6-4 (All Fx values in N, My =1N).

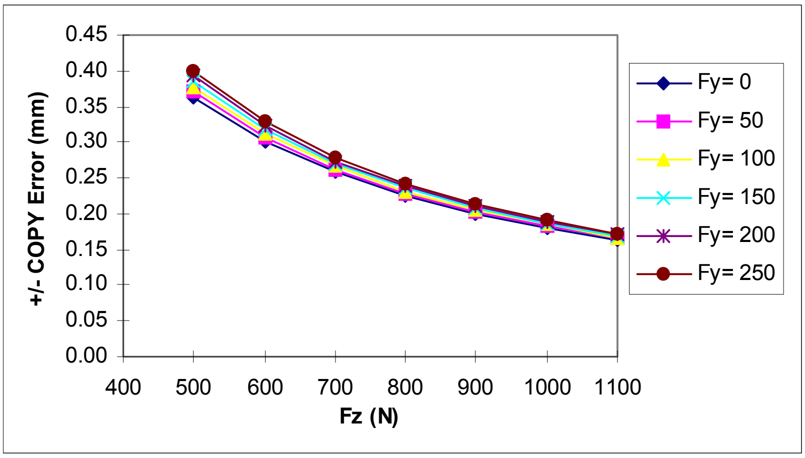


Figure 5.1.1.1.5: Relationship between increasing values of Fy and Fz on quantisation error in COPy calculations for the AMTI LG6-4 (All Fy values in N, Mx =1N).

5.1.1.1.2 Kistler 9287A Force Plate

5.1.1.1.2.1 Propagation of quantisation error in a single measure of COP using 12-bit ADC

Quantisation error in data obtained using the Kistler 9287A force plate was also calculated for comparison purposes and because this force plate has been used in previous shooting research (eg. Era *et al.*, 1996; Mason *et al.*, 1990; Niinimaa and McEvoy, 1983).

Measured values for each channel for the Kistler force plate have been calculated to coincide with the values used in the AMTI error analysis to facilitate direct comparison. As Kistler plates output eight channels of force data only, as opposed to AMTI's three channels of force data and three channels of moment data, channel values have been mathematically established to return the same forces and moments as the AMTI plate did. Values for individual channels are reasonable but are not based on test data. These values, along with minimum quantisation steps and error due to quantisation (quantisation error) for each Kistler force channel are included in table 5.1.1.4.

Type Kistler 9287A

12-bit ADC

Range: Fz = 500N

Range: Fx, Fy = 200N

Dimensions 600mm X 900 mm

Table 5.1.1.4: Quantisation step*, error and example values for the KISTLER 9287A force plate

	Minimum quantisation step (N)	Quantisation error (± N)	Measured values (N)
Fz1	**0.244**	**0.122**	**187**
Fz2	**0.244**	**0.122**	**222**
Fz3	**0.244**	**0.122**	**291**
Fz4	**0.244**	**0.122**	**50**
Fy1	**0.098**	**0.049**	**0.5**
Fy2	**0.098**	**0.049**	**0.5**
Fx1	**0.098**	**0.049**	**1**
Fx2	**0.098**	**0.049**	**1**

* Minimum quantisation step refers to the smallest quantisation step or unit for each channel.

NB (manufacturer specified and assumed constant for this analysis)

a = 0.200 m (distance from y-axis to transducer axis)

b = 0.350 m (distance from x-axis to transducer axis)

Dz = -0.045 m

(data from Kistler, 1984, manual)

Error associated with COPx:

The moment about the y-axis (My) is calculated by:

$$My = a * (-Fz1 + Fz2 + Fz3 - Fz4)$$

Using values from Table 5.1.1.4:

$$My = 0.200 * (-187 + 222 + 291 - 50)$$

$$My = 55 \text{ Nm}$$

Error associated with My:

$$|\delta My| \leq a * (|\delta Fz1 + |\delta Fz2| + |\delta Fz3| + |\delta Fz4|)$$

$$|\delta My| \leq 0.200 * (0.122 + 0.122 + 0.122 + 0.122)$$

$$|\delta My| \leq 0.0976 \text{ Nm}$$

Total force along the x-axis (Fx) is calculated by:

$$Fx = Fx1 + Fx2$$

Using values from Table 5.1.1.4:

$$Fx = 1 + 1$$

$$Fx = 2 \text{ N}$$

Error associated with Fx:

$$|\delta Fx| \leq |\delta Fx1| + |\delta Fx2|$$

$$|\delta Fx| \leq 0.049 + 0.049$$

$$|\delta Fx| \leq 0.098$$

*(referring to eqn 5.1) Let (Fx * Dz) = A*

Using values from Table 5.1.1.4:

$$A = 2 * -0.045$$

$$A = -0.09 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fx| * Dz$$

$$|\delta A| \leq 0.098 * 0.045$$

$$|\delta A| \leq 0.0044$$

*(referring to eqn 5.1) Let My - (Fx * Dz) = B*

Using values from Table 5.1.1.4:

$$B = -My + A$$

$$B = -55 + -0.09$$

$$B = -55.09 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta My| + |\delta A|$$

$$|\delta B| \leq 0.0976 + 0.0044$$

$$|\delta B| \leq 0.102 \text{ Nm}$$

Recalling eqn 5.1

$$COPx = \frac{-My + (Fx * Dz)}{Fz}$$

The value of COPx, using the values from Table 5.1.1.4:

From previous definition, -My + (Fx * Dz) = B

$$COPx = \frac{B}{Fz}$$

$$COPx = \frac{-55.09}{750}\, m$$

$$COPx = -0.07345m$$

Error associated with COPx:

$$\left|\frac{\delta COPx}{COPx}\right| \le \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

$$\left|\frac{\delta COPx}{COPx}\right| \le \left|\frac{0.102}{-55.09}\right| + \left|\frac{0.488}{750}\right|$$

$$\left|\frac{\delta COPx}{COPx}\right| \le 0.185\% + 0.065\% \le 0.250\%$$

Thus

COPx = -0.07345m ± 0.000184m

or

$$\boxed{\text{COPx} = -73.4 \text{ mm} \pm 0.2\text{mm}}$$

Error associated with COPy:

The moment about the x-axis (Mx) is calculated by:

Mx = b * (Fz1 + Fz2 - Fz3 - Fz4)

Using values from Table 5.1.1.4:

Mx = 0.350 * (187 + 222 - 291 - 50)

Mx = 24 Nm

Error associated with Mx:

$|\delta Mx| \le b * (|\delta Fz1| + |\delta Fz2| + |\delta Fz3| + |\delta Fz4|)$

$|\delta Mx| \le 0.350 * (0.122 + 0.122 + 0.122 + 0.122)$

$|\delta Mx| \le 0.171$ Nm

Total force along the y-axis (Fy) is calculated by:

$$Fy = Fy1 + Fy2$$

Using values from Table 5.1.1.4:

$$Fy = 0.5 + 0.5$$

$$Fy = 1 \text{ N}$$

Error associated with Fy:

$$|\delta Fy| \leq |\delta Fy1| + |\delta Fy2|$$

$$|\delta Fy| \leq 0.049 + 0.049$$

$$|\delta Fy| \leq 0.098 \text{ N}$$

*(referring to eqn 5.2) Let (Fy * Dz) = A*

Using values from Table 5.1.1.4:

$$A = 1 * -0.045$$

$$A = -0.045 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fy| * Dz$$

$$|\delta A| \leq 0.098 * 0.045$$

$$|\delta A| \leq 0.0044 \text{ Nm}$$

*(referring to eqn 5.2) Let Mx - (Fy * Dz) = B*

Using values from Table 5.1.1.4:

$$B = Mx - A$$

$$B = 24 - (-0.045)$$

$$B = 24.045 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta Mx| + |\delta A|$$

$$|\delta B| \leq 0.171 + 0.0044$$

$$|\delta B| \leq 0.1754 \text{ Nm}$$

Recalling eqn 5.2

$$COP(Y) = \frac{Mx - (Fy * Dz)}{Fz}$$

The value of COPy, using the values from Table 5.1.1.4:

From previous definition, Mx - (Fy * Dz) = B

$$COPy = \frac{B}{Fz}$$

$$COPy = \frac{24.045}{750}\,m$$

$$COPy = 0.03206m$$

Error associated with COPy:

$$\left|\frac{\delta COPy}{COPy}\right| \leq \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

$$\left|\frac{\delta COPy}{COPy}\right| \leq \left|\frac{0.171}{24.045}\right| + \left|\frac{0.488}{750}\right|$$

$$\left|\frac{\delta COPy}{COPy}\right| \leq 0.711\% + 0.065\% \leq 0.776\%$$

Thus

$$\text{COPy} = 0.03206\text{m} \pm 0.000249\text{m}$$

or

$$\boxed{\text{COPy} = 32.1 \text{ mm} \pm 0.2 \text{ mm}}$$

Based on this calculation, the shooter's COP at this particular instant of measurement is located at the co-ordinates (-73.4±0.1mm, 32.1±0.2mm). Quantisation error of ±0.1mm in the x-axis and ±0.2mm in the y-axis exists in this measure. As mentioned earlier, while not high relative to the absolute COP measure, the errors are high relative to measurements encountered in shooting. These values are slightly smaller than the error propagated from the AMTI force plates (0.2mm, 0.3mm). This is due to different amplifier settings, the slightly different calculation procedures and different sizes of these plates. This will be discussed in section 5.1.1.1.3.

5.1.1.1.2.2 Propagation of quantisation error with changing COP values using 12-bit ADC

Table 5.1.1.5 reports the quantisation error in COP, calculated from different Fz, Mx and My values obtained from a Kistler 9287A force plate. As the moment values increase, the error due to quantisation that is propagated in the calculation increases. Also, as Fz increases, quantisation error decreases. A similar effect was evident in the AMTI LG6-4 force plate, as expected, as these errors are calculation, rather than force plate dependent.

Table 5.1.1.5: Quantisation error in COP calculations for a range of Fz, Mx and My values for the Kistler 9287A output (Fx, Fy = 1N)

	My 0Nm	Mx 0Nm	My 100Nm	Mx 100Nm	Maximum My (val in brackets, Nm)	Maximum Mx (val in brackets, Nm)
Fz (N)	± COPx mm	± COPy mm	± COPx mm	± COPy mm	± COPx mm	± COPy mm
500	**0.204**	**0.351**	**0.400**	**0.546**	**0.496 (150)**	**0.790 (225)**
600	**0.170**	**0.292**	**0.306**	**0.428**	**0.415 (180)**	**0.658 (270)**
700	**0.146**	**0.250**	**0.246**	**0.350**	**0.355 (210)**	**0.564 (315)**
800	**0.128**	**0.219**	**0.204**	**0.295**	**0.310 (240)**	**0.494 (360)**
900	**0.113**	**0.195**	**0.174**	**0.255**	**0.276 (270)**	**0.439 (405)**
1000	**0.102**	**0.175**	**0.151**	**0.224**	**0.249 (300)**	**0.395 (450)**
1100	**0.093**	**0.159**	**0.133**	**0.200**	**0.226 (330)**	**0.359 (495)**

This effect is presented graphically in figures 5.1.1.6 and 5.1.1.7. The negative slope of each curve represents the decrease in quantisation error as Fz increases. The separation of each line represents the difference in quantisation error due to different moment values used in calculations, with a larger moment value associated with a larger quantisation error.

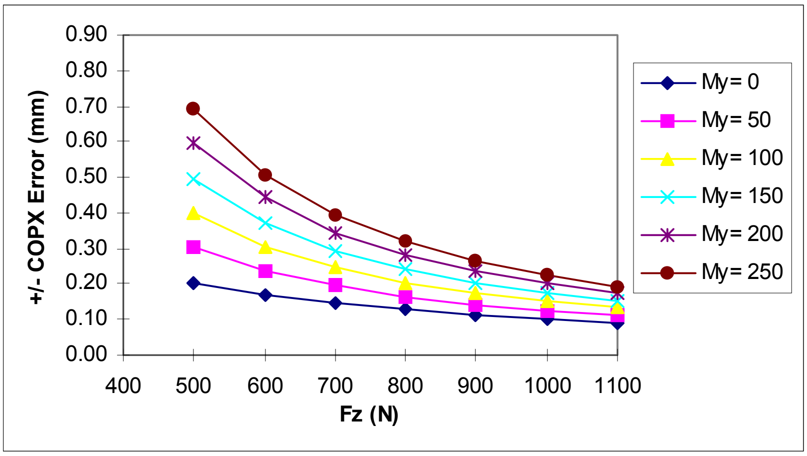


Figure 5.1.1.6: Relationship between increasing values of My and Fz on quantisation error in COPx calculations for the Kistler 9287A

(All My values in Nm, Fx,Fy=1N).

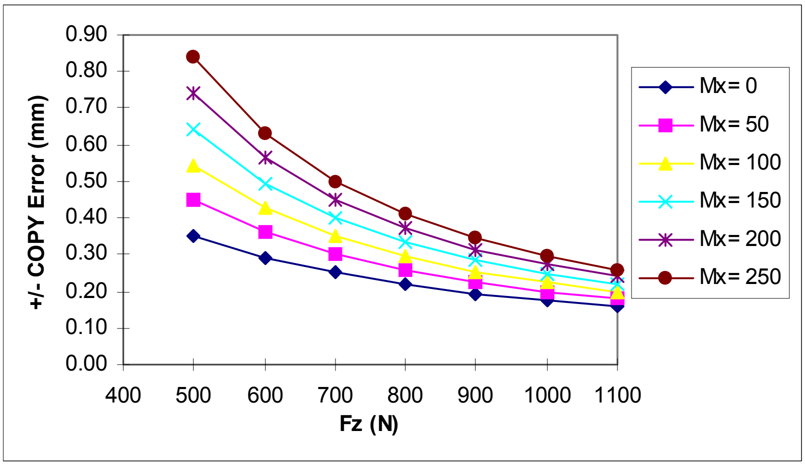


Figure 5.1.1.7: Relationship between increasing values of Mx and Fz on quantisation error in COPy calculations for the Kistler 9287A

(All My values in Nm, Fx,Fy=1N).

Table 5.1.1.6 reports the quantisation error in COP calculations for a range of Fz, Fx and Fy values. The increase in COP quantisation error when Fx and Fy values were increased was small, indicating that these variables influence quantisation error minimally in COP calculations. For example, error increased by only 0.035mm between COP calculated when Fx=0N (±0.205mm) to Fx=400N (±0.240mm) for Fz=500N. The errors reported in table 5.1.1.6 were all slightly smaller than those using the AMTI LG6-4 force plate (table 5.1.1.3).

Table 5.1.1.6: Quantisation error in COP calculations for a range of Fz, Fx and Fy values for the Kistler 9287A (Mx, My=1Nm)

	Fx=0Nm	Fy=0Nm	Fx=100Nm	Fy=100Nm	Maximum Fx (400N)	Maximum Fy (400N)
Fz (N)	± COPx mm	± COPy mm	± COPx mm	± COPy mm	± COPx mm	± COPy mm
500	**0.205**	**0.353**	**0.214**	**0.361**	**0.240**	**0.388**
600	**0.171**	**0.294**	**0.177**	**0.300**	**0.195**	**0.318**
700	**0.146**	**0.251**	**0.151**	**0.256**	**0.164**	**0.269**
800	**0.128**	**0.220**	**0.131**	**0.223**	**0.142**	**0.234**
900	**0.114**	**0.195**	**0.116**	**0.198**	**0.125**	**0.206**
1000	**0.102**	**0.176**	**0.105**	**0.178**	**0.111**	**0.185**
1100	**0.093**	**0.160**	**0.095**	**0.162**	**0.100**	**0.167**

This effect is presented graphically in figures 5.1.1.8 and 5.1.1.9. Each curve represents the quantisation error in COP for different Fx and Fy values. Once again, the negative slope of each curve represents the decrease in quantisation error as Fz increases. The separation of each curve is small, indicating minimal effect on error due to changes in horizontal force values.

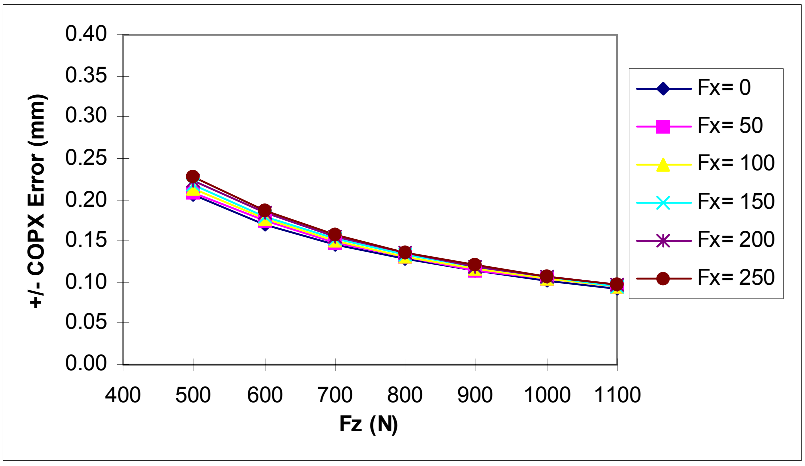


Figure 5.1.1.8 Relationship between increasing values of Fx and Fz on quantisation error in COPx calculations for the Kistler 9287A (All Fx values in N, My =1N).

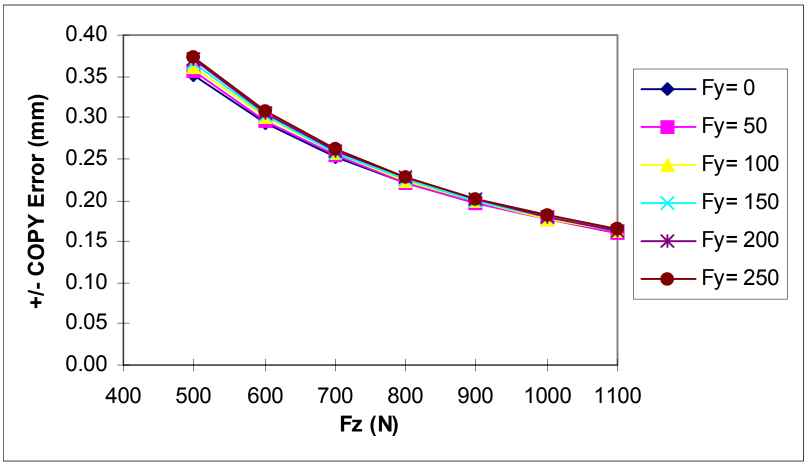


Figure 5.1.1.9 Relationship between increasing values of Fy and Fz on quantisation error in COPy calculations for the Kistler 9287A (All Fy values in N, Mx =1N).

5.1.1.1.3 Comparison of error propagation for AMTI LG6-4 and Kistler 9287A force plates using 12-bit ADC

Overall, data obtained from the Kistler 9287A produced less error due to quantisation in COP calculations than the AMTI LG6-4. This difference is due to the combined effects of three factors that differ between the systems. Amplifier gains available in the Kistler system were larger than those on the AMTI system. Also, individual channels are passed through the ADC process before they are summed in the Kistler system, as opposed to the AMTI system, in which single channels for Fz, Mx and My are passed through the ADC process. Both these factors effectively increase the range and resolution of measurement that is obtainable. Further, the Kistler 9287A (900mm x 600mm) is slightly smaller than the AMTI LG6-4 (1200mm x 600mm). Basically, while the same number of measurement steps are used but across a larger distance in the AMTI LG6-4, increasing the minimum measurement step and increasing the error due to quantisation as a result. However, it should be pointed out that a number of studies using the Kistler force plates to assess COP have used smaller gains. Mason *et al.* (1990) used settings of 1000N for Fz channels and 500N for Fx and Fy channels to measure body sway in pistol shooters. These settings will increase the error estimations presented in the previous sections by a factor of approximately two.

5.1.2 COP Resolution

5.1.2.1 COP resolution for the AMTI LG6-4 using 12-bit ADC

The equations below calculate the approximate COP resolution for a range of Fz values between 500N and 1100N (summarised in table 5.1.2.1 at the end of calculations). The method of calculation was reported in the methodology section (4.1.1.2) and has been repeated here for clarity. Also for clarity, two terms are redefined. Measurement step has been used to refer to the minimum step, or unit, that COP is measured in. Quantisation step refers to the minimum step, or unit, that the ADC system samples the data. Measurement step is distinct from quantisation step as it involves calculation after the quantisation process at the ADC. However, it is directly related to the quantisation step size.

$$\text{COPx (measurement step)} \quad = \frac{My(measurement.\,step)}{Fz(SubjectWeight)}$$

$$\text{COPy (measurement step)} \quad = \frac{Mx(measurement.\,step)}{Fz(SubjectWeight)}$$

Where Mx = 0.34Nm and My = 0.24Nm (from table 5.1.1)

Where Fz = 500N

COPx (measurement step) $= \frac{0.24}{500}$ = 0.480mm

COPy (measurement step) $= \frac{0.34}{500}$ = 0.680mm

Where Fz = 600N

COPx (measurement step) $= \frac{0.24}{600}$ = .0400mm

COPy (measurement step) $= \frac{0.34}{600}$ = 0.567mm

Where Fz = 700N

COPx (measurement step) $= \frac{0.24}{700}$ = 0.343mm

COPy (measurement step) $= \frac{0.34}{700}$ = 0.486mm

Where Fz = 800N

COPx (measurement step) $= \frac{0.24}{800}$ = 0.300mm

COPy (measurement step) $= \frac{0.34}{800}$ = 0.425mm

Where Fz = 900N

COPx (measurement step) $= \frac{0.24}{900}$ = 0.267mm

COPy (measurement step) $= \frac{0.34}{900}$ = 0.378mm

Where Fz = 1000N

COPx (measurement step) $= \frac{0.24}{1000}$ = 0.240mm

COPy (measurement step) $= \frac{0.34}{1000}$ = 0.340mm

Where Fz = 1100N

COPx (measurement step) $= \dfrac{0.24}{1100}$ $= 0.218\text{mm}$

COPy (measurement step) $= \dfrac{0.34}{1100}$ $= 0.309\text{mm}$

*** Where Fz = 750N**

COPx (measurement step) $= \dfrac{0.24}{750}$ $= 0.320\text{mm}$

COPy (measurement step) $= \dfrac{0.34}{750}$ $= 0.453\text{mm}$

Table 5.1.2.1 summarises the COP resolution for different values of Fz, as calculated above. As can be noted from the table, as Fz increases, the resolution in which COP is measured increases, or the minimum measurement step decreases. These measurement steps are dependent only on the resolution of the force plate ADC system and the shooter's effective weight (shooter, shooting clothing, gun). These measurement steps are high relative to the displacements of 2mm to 4mm that have been reported in shooting research (eg. Mason *et al.*, 1990; Viitasalo *et al.*, 1997). This will be discussed in more detail in section 5.1.3.1.1. Also, the different measurement steps or resolution in which COP is measured for different body weights also highlights the problem reported by Wisleder and McLean (1991) that subjects with different body weights will be measured with different resolutions.

Table 5.1.2.1: COP resolution (measurement steps) AMTI LG6-4 force plate

Fz (N)	COPx (mm)	COPy (mm)
500	**0.480**	**0.680**

600	**0.400**	**0.567**
700	**0.343**	**0.486**
800	**0.300**	**0.425**
900	**0.267**	**0.378**
1000	**0.240**	**0.340**
1100	**0.218**	**0.309**
*750	*0.320	*0.453

For the 750N shooter used in the error proofs, COP will be measured in steps of 0.320 mm and 0.453 mm for x and y axes respectively when using 12-bit ADC. Mason *et al.* (1990) reports mean COP ranges for pistol shooters of 3.3mm perpendicular to the line of shot (x-axis) and 3.1mm parallel to the line of shot (y-axis). This COP range would be measured across only 11 measurement steps in the x-axis and 6 measurement steps in the y-axis. Obviously smoothing techniques can reduce error associated with quantisation error in this measurement if data has been sampled over a period of time. However, the poor resolution underlying the measure will limit the ability of these techniques to represent the underlying signal accurately. As such, the discrepancy between actual and measured values may remain relatively large.

This poor COP resolution provided by 12-bit ADC data has implications for the measurement of postural sway in shooters. It is likely that the difference in postural control of elite level shooters will lie within only a few measurement steps. This would make comparison of body sway between elite shooters or good and bad shots for individuals difficult, as the ability to detect differences is decreased. This resolution would also allow for only a coarse description of the COP path for non-shooters generally, who have been reported as producing COP ranges as low as 3 to 6 mm (eg. Ekdahl *et al.*, 1991). Any COP parameter calculated from 12-bit ADC data, such as COP lengths and speeds, will also suffer considerably from this low resolution. This is discussed in more detail in section 5.1.4.

5.1.2.2 COP resolution for the Kistler 9287A using 12-bit ADC

The equations below calculate the approximate COP resolution for Fz ranges from 500N to 1100N for the Kistler 9287A. These values are summarised in table 5.1.2.2.

$$\text{COPx (measurement step)} = \frac{My(measurement.step)}{Fz(SubjectWeight)}$$

$$\text{COPy (measurement step)} = \frac{Mx(measurement.step)}{Fz(SubjectWeight)}$$

The minimum measurement step for Mx and My using the Kistler 9287A will be:

Recalling

$$Mx = b * (Fz1 - Fz2 + Fz3 - Fz4) \text{ and}$$

$$My = a * (-Fz1 + Fz2 + Fz3 - Fz4)$$

One measurement step for Mx and My while maintaining the same Fz value requires that an increase by one quantisation step in one Fz channel must be offset with the decrease by one quantisation step in another Fz channel. For example, in the case of COPx, an increase in Fz1 of one quantisation step would require Fz2 or Fz4 to decrease by one quantisation step to maintain the same Fz value. Thus, the measurement step of Mx and My will be:

Mx (measurement step) = b * (2* Fz(minimum quantisation step))

Using the Fz(minimum quantisation step) value from Table 5.1.1.4 and the b value given earlier:

$$Mx = 0.35 * (2 * 0.244) \quad = 0.171 \text{ Nm}$$

My (measurement step) = a * (2* Fz(minimum quantisation step))

Using the Fz(minimum quantisation step) value from Table 5.1.1.4 and the b value given earlier:

$$My = 0.20 * (2 * 0.244) \quad = 0.098 \text{ Nm}$$

Where Fz = 500N

$$\text{COPx (measurement step)} = \frac{0.098}{500} = 0.195\text{mm}$$

$$\text{COPy (measurement step)} = \frac{0.171}{500} = 0.342\text{mm}$$

Where Fz = 600N

$$\text{COPx (measurement step)} = \frac{0.098}{600} = 0.163\text{mm}$$

$$\text{COPy (measurement step)} = \frac{0.171}{600} = 0.285\text{mm}$$

Where Fz = 700N

$$\text{COPx (measurement step)} = \frac{0.098}{700} = 0.140\text{mm}$$

$$\text{COPy (measurement step)} = \frac{0.171}{700} = 0.244\text{mm}$$

Where Fz = 800N

$$\text{COPx (measurement step)} = \frac{0.098}{800} = 0.122\text{mm}$$

$$\text{COPy (measurement step)} = \frac{0.171}{800} = 0.214\text{mm}$$

Where Fz = 900N

COPx (measurement step) $= \dfrac{0.098}{900} = 0.109\text{mm}$

COPy (measurement step) $= \dfrac{0.171}{900} = 0.190\text{mm}$

Where Fz = 1000N

COPx (measurement step) $= \dfrac{0.098}{1000} = 0.098\text{mm}$

COPy (measurement step) $= \dfrac{0.171}{1000} = 0.171\text{mm}$

Where Fz = 1100N

COPx (measurement step) $= \dfrac{0.098}{1100} = 0.089\text{mm}$

COPy (measurement step) $= \dfrac{0.171}{1100} = 0.155\text{mm}$

*** Where Fz = 750N**

COPx (measurement step) $= \dfrac{0.098}{750} = 0.131\text{mm}$

COPy (measurement step) $= \dfrac{0.171}{750} = 0.229\text{mm}$

Table 5.1.2.2 summarises the COP resolution for different values of Fz, as calculated above. As for the AMTI plate, as Fz increases, COP resolution increases. The Kistler 9287A shows smaller measurement steps than the AMTI LG6-4. As such, the Kistler force plate will measure COP with greater resolution than the AMTI. The factors affecting this difference were discussed in section 5.1.1.1.3.

Table 5.1.2.2: COP resolution (measurement steps) Kistler 9287A force plate

Fz (N)	COPx (mm)	COPy (mm)
500	**0.195**	**0.342**
600	**0.163**	**0.285**
700	**0.140**	**0.244**
800	**0.122**	**0.214**
900	**0.109**	**0.190**
1000	**0.098**	**0.171**
1100	**0.089**	**0.155**
*750	*0.131	*0.229

* resolution of 750N included for consistency with error calculations in section 5.1

5.1.3 Comparison of 12-bit and 16-bit ADC

5.1.3.1 Quantisation error and resolution for single COP measures using the AMTI LG6-4

As mentioned earlier, 12-bit ADC systems offer 4096 quantisation steps. 16-bit ADC systems offer 65536 steps. A basic set-up will entail half of these points measuring in the positive and half in the negative direction, or a full range of ±2048 for 12-bit ADC and ±32768 steps for 16-bit ADC. This increase will obviously improve resolution during analogue to digital conversion and reduce quantisation error.

Tables 5.1.3.1 and 5.1.3.2 compare 12-bit and 16-bit ADC in COP calculation error and approximate step for the AMTI LG6-4 plate. The 12-bit data has been reported in earlier sections and is repeated here. Also, the level of significance to which numbers have been rounded is probably not obtainable and have been reported as such for purposes of comparison only. In tables 5.1.3.1 and 5.1.3.3, error values for 16-bit data have been calculated as for 12-bit data in previous sections (5.1.1.1.1 and 5.1.1.2.1).

Minimum measurement steps have been calculated also as detailed in the previous sections (5.1.2.1 and 5.1.2.2).

Table 5.1.3.1: Comparison of 12-bit and 16-bit ADC using the AMTI LG6-4: Error due to quantisation in COP calculations for a range of Fz values (Mx,My = 1Nm, Fx,Fy = 1N)

Fz (N)	12-bit ± COPx (mm)	16-bit ± COPx (mm)	12-bit ± COPy (mm)	16-bit ± COPy (mm)
500	**0.263**	**0.016**	**0.363**	**0.023**
600	**0.219**	**0.014**	**0.302**	**0.019**
700	**0.187**	**0.012**	**0.259**	**0.016**
800	**0.164**	**0.010**	**0.226**	**0.014**
900	**0.145**	**0.009**	**0.201**	**0.013**
1000	**0.131**	**0.008**	**0.181**	**0.011**
1100	**0.119**	**0.007**	**0.164**	**0.010**

Table 5.1.3.2: Comparison of 12-bit and 16-bit ADC using the AMTI LG6-4: approximate measurement steps of COP for a range of Fz values

Fz (N)	12-bit COPx (mm)	16-bit COPx (mm)	12-bit COPy (mm)	16-bit COPy (mm)
500	**0.480**	**0.030**	**0.680**	**0.043**
600	**0.400**	**0.025**	**0.567**	**0.035**
700	**0.343**	**0.021**	**0.486**	**0.030**
800	**0.300**	**0.019**	**0.425**	**0.027**
900	**0.267**	**0.017**	**0.378**	**0.024**
1000	**0.240**	**0.015**	**0.340**	**0.021**
1100	**0.218**	**0.014**	**0.309**	**0.019**

As can be noted from tables 5.1.3.2. and 5.1.3.3, quantisation errors will be reduced quite markedly (by a factor of 16) using force plate data passed through a 16-bit ADC system compared to a 12-bit ADC system. For example, a 700N subject will be measured with an error of ±0.187mm and ±0.259mm for COPx and COPy respectively using a 12-bit ADC system. Using a 16-bit ADC system, this error will be reduced to ±0.012mm and ±0.016mm for COPx and COPy respectively. The approximate resolution of COP for the same subject improves from 0.343mm to 0.021mm in COPx and from 0.486mm to 0.030mm in COPy.

As reported earlier, Mason *et al.* (1990) found COP ranges for elite pistol shooters of 3.3mm and 3.1mm for COPx and COPy respectively. Using this data and the COP measurement steps from table 5.1.2.1, 12-bit ADC would provide 8 to 13 measurement steps for COPx and 5 to 10 measurement steps for COPy. This resolution is unacceptable for any within group analysis. For the same amount of COP movement, 16-bit ADC would provide between 180 and 330 steps of measurement for COPx measurement and 77 to 155 steps of measurement for COPy. Errors for shooters weighing between 600N-1000N (likely values for shooters) would be ±0.131mm to ±0.302mm in COPx and ±0.181 to ±0.302mm in COPy. These errors are quite high relative to the measures reported in the Mason *et al.* study. This error is reduced to ±0.014mm for COPx and ±0.019mm for COPy using 16-bit data. The resolution achieved using 16-bit ADC will provide adequate precision for analysis of COP movement of pistol shooting.

Also mentioned earlier, Viitasalo *et al.* (1997) reports COP ranges of 1.92 - 2.54mm in the x-axis and 1.78 - 2.04mm in the Z axis (equivalent to COPx and COPy respectively in the Mason *et al.*, 1990, study) for running target rifle shooters. These ranges are smaller than those reported by Mason et al. for pistol shooters. As such, the issues of error and resolution will be even more influential to measurement. 12-bit ADC would measure this data across only 3-11 steps, while 16-bit data would use approximately 50-130 steps. Errors would be the same as those reported in the previous paragraph.

The poor resolution and error propagated in 12-bit ADC data makes it inadequate for posture assessment of shooters. For comparison between groups of different skill level, 12-bit ADC may provide adequate data. Also, the effects of this poor resolution and large error due to quantisation will be reduced when averaged across a large number of shots or across a large number of shooters. However, for analyses dealing with elite shooters, the likelihood of finding differences or relationships between body sway as measured by COP and shooting performance is remote. Further, the lack of precision provided by 12-bit ADC makes it effectively unusable for body sway assessment of elite shooters. The precision provided by 16-bit ADC will provide far better estimations of COP movement in shooting. Further, it will increase the chance of finding any differences in posture control, as measured by COP, between elite shooters and between good and bad shots of elite shooters.

5.1.3.2 Quantisation error and resolution for single COP measures using the Kistler 9287A

Tables 5.1.3.3 and 5.1.3.4 compare 12-bit and 16-bit ADC in COP calculation error and approximate step for the Kistler 9287A force plate. In the case of 12-bit ADC, the level of significance to which numbers have been rounded is probably not obtainable and have been reported as such for purposes of comparison only.

Table 5.1.3.3: Comparison of 12-bit and 16-bit ADC using the Kistler 9287A: Quantisation error in COP calculations for a range of Fz values

(Mx,My = 1Nm, Fx,Fy = 1N)

Fz (N)	12-bit ± COPx (mm)	16-bit ± COPx (mm)	12-bit ± COPy (mm)	16-bit ± COPy (mm)
500	**0.204**	**0.013**	**0.351**	**0.022**
600	**0.170**	**0.011**	**0.292**	**0.018**
700	**0.146**	**0.009**	**0.250**	**0.016**
800	**0.128**	**0.008**	**0.219**	**0.014**
900	**0.113**	**0.007**	**0.195**	**0.012**
1000	**0.102**	**0.006**	**0.175**	**0.011**
1100	**0.093**	**0.006**	**0.159**	**0.010**

Table 5.1.3.4: Comparison of 12-bit and 16-bit ADC using the Kistler 9287A: approximate measurement steps of COP for for a range of Fz values

Fz (N)	12-bit COPx (mm)	16-bit COPx (mm)	12-bit COPy (mm)	16-bit COPy (mm)
500	**0.195**	**0.012**	**0.342**	**0.021**
600	**0.163**	**0.010**	**0.285**	**0.018**
700	**0.140**	**0.009**	**0.244**	**0.015**
800	**0.122**	**0.008**	**0.214**	**0.013**
900	**0.109**	**0.007**	**0.190**	**0.012**
1000	**0.098**	**0.006**	**0.171**	**0.011**
1100	**0.089**	**0.006**	**0.155**	**0.010**

Using the same value of Fz as used in the AMTI example, the measurement of COP of a 700N subject using the Kistler 9287A force plate and maximum gain will have an error of ±0.140mm and ±0.244 mm for COPx and COPy respectively using a 12-bit ADC system. Using a 16-bit system, this error will be reduced to ±0.009mm and ±0.015mm. The approximate resolution of COP for the same subject improves from 0.140mm to 0.009mm in COPx and from 0.244mm to 0.015mm in COPy. Errors are slightly lower and resolution is slightly better for the Kistler 9287A compared with the AMTI LG6-4 (table 5.1.3.1 and 5.1.3.2). The reasons for this difference have been discussed earlier (section 5.1.1.1.3).

For the same COP range data reported above for elite pistol shooters (Mason *et al.*, 1990) of 3.1mm and 3.3mm for COPx and COPy respectively and assuming subjects weight between 600 N and 1000N, the Kistler 9287A force plate using 12-bit ADC would provide between 19 and 32 steps of measurement for COPx and 12 to 19 steps of measurement for COPy. Maximum error approximates for the same data using 12-bit ADC would be ±0.102 to ±0.170mm in COPx and ±0.175 to ±0.292mm in COPy. Using 16-bit ADC, there would be 310 to 517 measurement steps for COPx and 183 to 300 for COPy. Errors for the Fz range of 600N-1000N would be reduced to between ±0.006 and ±0.011mm for COPx and between ±0.011 and ±0.018mm for COPy. Using the rifle shooting data from above, 16-bit ADC would measure this data across approximately 99-423 steps, while 12-bit data would use only 6-26 steps. Errors would be the same as those reported above.

5.1.4 Errors due to quantisation in parameters used in this study

Error calculations presented previously have been based on the calculation of a single COP measure only. However, the majority of postural sway measures in shooting and other applications involve monitoring COP or horizontal forces over a set period of time. The following analysis quantifies errors due to, or related to, quantisation problems.

5.1.4.1 Theoretical basis and calculation of error propagation in parameters used in this study

The parameters used to assess body sway in this study can be categorised by actual (and derived) measures and statistical measures. Actual and derived measures include single measures, ranges and length. Statistical measures include averages and standard deviations. This section addresses the effects of quantisation error and quantifies this error for these categories. Also, within each category, an example proof for error estimations and approximate measurement steps using 12-bit ADC data to calculate parameters, where appropriate, is presented. Full proofs are included in Appendix B. Similar calculations were performed on parameters using 16-bit data which simply involved replacing the 12-bit error and measurement step data with the 16-bit data. Calculations of error and measurement step using 16-bit ADC data are not reported here.

Error and measurement step values for both 12-bit and 16-bit ADC have been summarised and presented in Tables 5.1.4.1 and 5.1.4.2 in the next section (5.1.4.2). Repeating for clarity, only errors and measurement steps for parameters measured from AMTI LG6-4 data have been calculated

5.1.4.1.1 Actual measures

Single measures: As shown in the previous section, single measures will be affected by quantisation error.

Example:

Fx and Fy are measured directly by the force plate and given in table 5.1.1.1 (repeated here for clarity). **= 0.37N**

As the ADC board directly measures Fx and Fy, quantisation error will be ±0.5 of the minimum measurement step **±0.185N**

Ranges: As the range measure is dependent only upon the two outermost (maximum and minimum) points the error associated with the range for a trial will involve only those two points. Hence, the maximum possible error due to quantisation during the calculation of range will be two times the error for a single measure. As detailed in methods section 4.1.1.1, a better approximation of this error will be obtained using quadrature summation (Taylor, 1982).

Example:

FxRange = Fx (max) - Fx (min)

The quantisation step of Fx is 0.37N, or +/- 0.185N.

$$\delta(\text{FxRange}) = \sqrt{(\delta Fx(\max))^2 + (\delta Fx(\min))^2}$$

$$= \sqrt{(0.185)^2 + (0.185)^2} \qquad = \mathbf{0.262N}$$

and will certainly be no more than

$$\delta(\text{FxRange}) \leq \delta\text{Fx (max)} + \delta\text{Fx (min)}$$

$$\leq 0.185 + 0.185 \qquad \leq \mathbf{0.370N}$$

Lengths: The length or excursion of the COP is calculated by finding the distance between corresponding points and summing them across the sample period. When examining the length of the COP trace in the X or Y axes, a number of possibilities exist. The simplest COP trace is a straight line, where the COP travels in only one direction during the sampling period. In this case, the length is effectively the range (see figure 5.1.4.1). As such, the maximum error is only dependent on the first and last, or maximum and minimum values of COP, and would be two times the error for a single measure. Locations that lie in between these values may suffer from error also, however, as the length between corresponding points is added, the error will be cancelled as the next length will have an equal amplitude of error but opposite direction. So, if one COP location is measured shorter than it is, the next will be measured longer and vice versa.

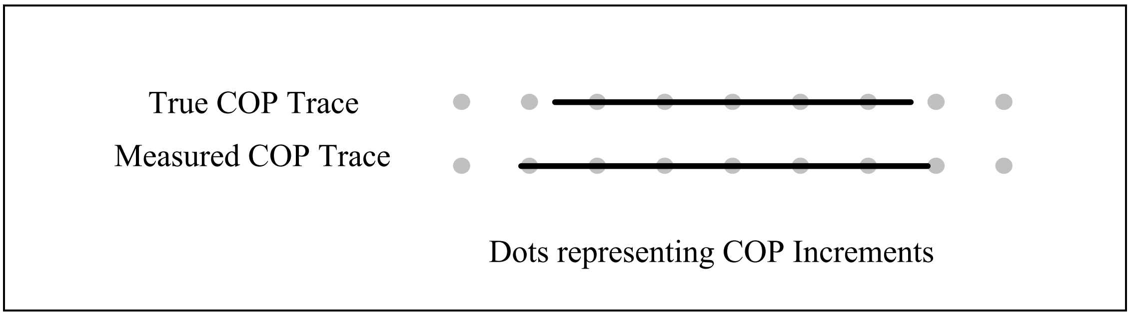


Figure 5.1.4.1: True and measured COP traces. The trace length will be in error only at each end of the trace (or 2 times error for a single measure).

Another potential COP path generated is a COP trace which oscillates backwards and forwards for each consecutive sample or a COP which is perfectly stationary (see figure 5.1.4.2). In this case, the error due to quantisation could be up to (n-1) times the error for a single measure across “n” samples, as each time the trace changes direction, the error due to quantisation can be propagated in the calculation. This is of particular importance in noisy signals, which may oscillate constantly regardless of COP path.

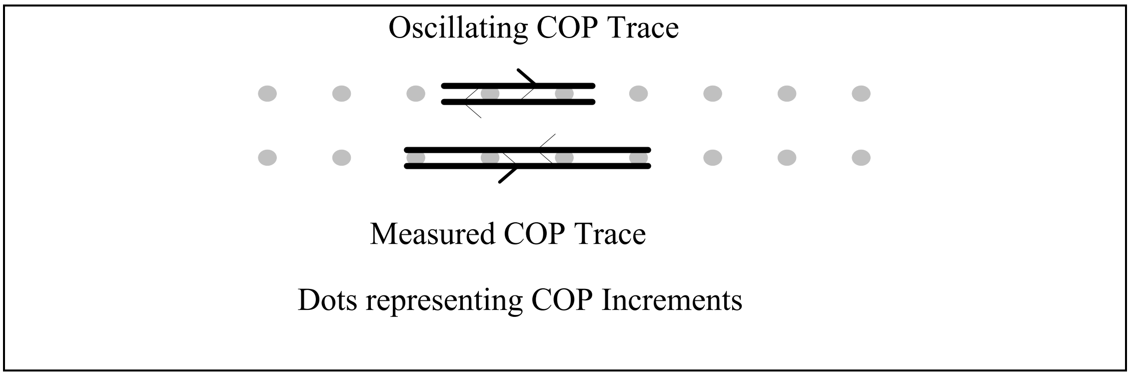


Figure 5.1.4.2: True and measured COP traces. The oscillating COP trace can be in error each time it changes direction.

Error = (n-1) times error for a single measure over 'n' measures.

Between these two possibilities is any number of changes of COP direction or periods where the COP is stationary. Only points at the change of direction of the COP trace or points associated with the COP remaining stationary will contribute to error. As mentioned earlier, during one directional movement, errors immediately cancel out. This makes approximating error in length measures difficult, as it would require knowledge of the COP trace, which could be expected to vary between trials and individuals. Calculations will detail the two extremes that may exist and a general approximation of error, which does not take into account the nature of the trace.

Example:

COPxLength

$$= \left(\sqrt{(COPx(2) - COPx(1))^2}\right) + \left(\sqrt{(COPx(3) - COPx(2))^2}\right) + ...$$

$$....+ \left(\sqrt{(COPx(n) - COPx(n-1))^2}\right)$$

Where n = number of points in sample

COPx1, COPx2... = 1st, 2nd .... measured location of COPx

COPy1, COPy2... = 1st, 2nd .... measured location of COPy

The error for the case where the path moves in one direction only depends on the first and last point measured. Hence the error will be two times the error for one point.

$$\delta\text{COPxLength} = \sqrt{(\delta COPx(first))^2 + (\delta COPx(last))^2}$$

$$= \sqrt{(0.243)^2 + (0.243)^2} \qquad \mathbf{= 0.344mm}$$

and will be no more than

$$\leq 0.243 + 0.243 \qquad \mathbf{\leq 0.486mm}$$

For the case of a stationary or constantly oscillating point:

$$\delta\text{COPxLength} = \delta\text{COPxLength (single)} * (n-1)$$

where n = no. of samples (128, 384 and 640)

δCOPxLength (single)

= error for one length measurement between consecutive points

= 0.344 mm or ≤ 0.486 mm

Maximum possible error in 1s will be

$$\delta\text{COPxLength 1 second} \leq 0.486 * (128-1) \qquad \mathbf{\leq 61.772\ mm}$$

The approximate error in 1s will equal (using quadrature summation)

$$\delta\text{COPxLength 1 second} = \sqrt{0.344^2 * (128 - 1)} \qquad \mathbf{= 3.877\ mm}$$

5.1.4.1.2 Statistical measures

Averages: Average is calculated by dividing the sum of values by the number of values. If quantisation errors are random, the error of each distance will be equally distributed about the true value and will largely be cancelled out during summation.

However, in the case of average speed, as for length measures, errors due to quantisation may be cancelled but may also be extremely large. Averaging the values will reduce the absolute, but not the relative magnitude of the error. A three point central difference method of calculating COP speed was used in this study which involves finding the distance between point (n-1) and point (n+1) and dividing by twice the time interval. Assuming that time is constant, the maximum error due to quantisation in a single measure of speed will be two times the error of a single COP displacement measure (as for range) divided by two times the time interval. Assuming that this error exists in each sample, when speed is averaged, the error in the measure is also the average error for each measure. As such, the error will be no larger than the error for a single speed measure, while the approximate error will be obtained using quadrature summation.

The possibility also exists for error in average values to occur due to limits of measure directly related to quantisation, although in practice it would be unlikely to occur in force plate measurements, as ADC boards generally fluctuate across a number of ADC units during measurement. In the case of a stationary value that lies, for example, half way between ADC units, it might be expected that the ADC board will fluctuate one unit either side of the true point. Averaging will accurately quantify the true value in this case. However, if the value lay either side of this point, theoretically the ADC would return the lower or higher unit only. This being the case, an error up to 0.49^{-} times the measurement step could occur (see figure 5.1.4.3). This may be classed as a systematic error, but is directly related to quantisation.

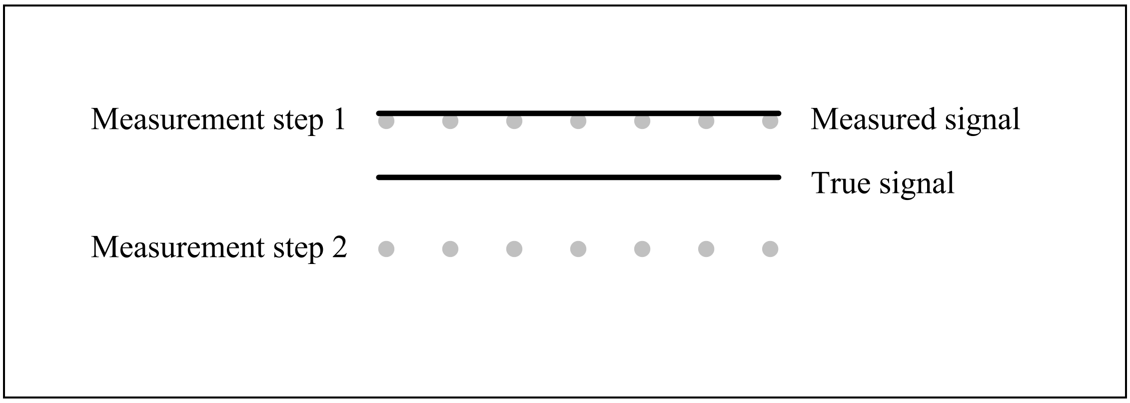


Figure 5.1.4.3: Error potential due to quantisation error in average measures.

Example:

COPAbsSpeedAve =

$$\frac{(COPAbsSpeed_1 + COPAbsSpeed_2 + \ldots + COPAbsSpeed)}{n}$$

Where $COPAbsSpeed_{1,2\ldots n}$ = COPAbs Speed values at n = 1,2..n

n = number of samples

δCOPAbs Speed Ave =

$$\frac{(\delta COPAbsSpeed_1 + \delta COPAbsSpeed_2 + \ldots + \delta COPAbsSpeed_n)}{n}$$

Where $\delta COPAbsSpeed_{1,2\ldots n}$ = COPAbs Speed error for a single measure

= 45.824mm/s

≤ 65.614 mm/s

Approximate error due to quantisation will be:

At n = 128 (1s)

δCOPAbs Speed Ave = (using quadrature)

$$\frac{\sqrt{\delta COPAbsSpeed_1^{\ 2} + \delta COPAbsSpeed_2^{\ 2} + ... + \delta COPAbsSpeed_{128}^{\ 2}}}{128}$$

$$= \frac{\sqrt{45.824_1^{\ 2} + 45.824_2^{\ 2} + ... + 45.824_{128}^{\ 2}}}{128} = \mathbf{4.050\ mm/s}$$

At n = 384 (3s)

δCOPAbs Speed Ave = (using quadrature)

$$\frac{\sqrt{\delta COPAbsSpeed_1^{\ 2} + \delta COPAbsSpeed_2^{\ 2} + ... + \delta COPAbsSpeed_{384}^{\ 2}}}{384}$$

$$= \frac{\sqrt{45.824_1^{\ 2} + 45.824_2^{\ 2} + ... + 45.824_{384}^{\ 2}}}{384} = \mathbf{2.338\ mm/s}$$

At n = 640 (5s)

δCOPAbs Speed Ave = (using quadrature)

$$\frac{\sqrt{\delta COPAbsSpeed_1^{\ 2} + \delta COPAbsSpeed_2^{\ 2} + ... + \delta COPAbsSpeed_{640}^{\ 2}}}{640}$$

$$= \frac{\sqrt{45.824_1^{\ 2} + 45.824_2^{\ 2} + ... + 45.824_{640}^{\ 2}}}{640}$$

$$= \mathbf{1.811\ mm/s}$$

And, in all measurement periods, will be no more than

$$\leq \frac{(\delta COPAbsSpeed_1 + \delta COPAbsSpeed_2 + ... + \delta COPAbsSpeed_n)}{n}$$

$$\leq \frac{(65.614 + 65.614 + ... + 65.614_n)}{n} \qquad \leq \mathbf{65.614 mm/s}$$

Standard deviations: Assuming quantisation is random, errors will again be cancelled in calculating the standard deviation. However, as for average measures, there is still potential influence for quantisation error to affect values. The methods of Taylor

(1982) have been employed to find the maximum and approximate error due to quantisation in standard deviation measures used in this study.

The possibility exists for error in standard deviation values due to limits of measure directly related to quantisation. In the case of a stationary value that lies, for example, half way between ADC units, it might be expected that the ADC board will fluctuate one unit either side of the true (see figure 5.1.4.4). In this case, the standard deviation would be greater than zero when in fact it was zero. This error is equal to the square root of half the measurement step of the parameter divided by 'n'. The error in standard deviation due to quantisation will be extremely small in both absolute and relative terms. Once again, it is unlikely that this will occur in force plate measurement.

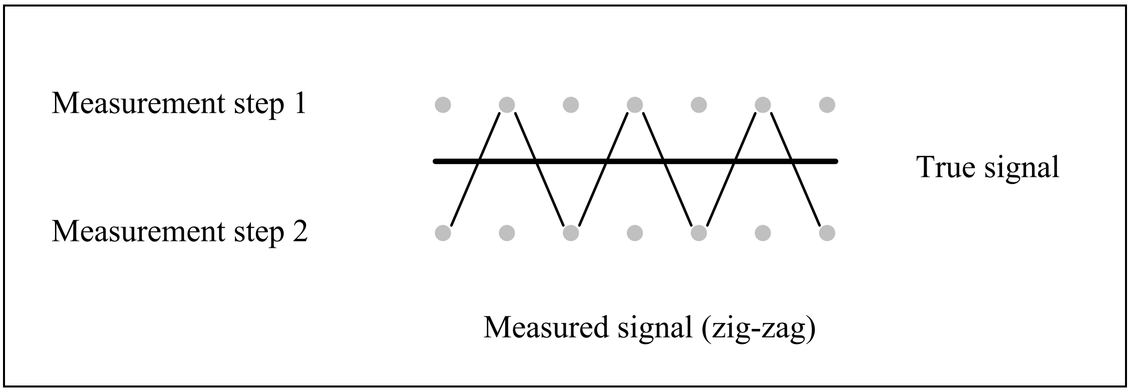


Figure 5.1.4.4: Error potential due to quantisation error in standard deviation measures.

Example:

$$\text{COPySD} = \sqrt{\frac{\sum (COPy - C\bar{O}Py)^2}{n - 1}}$$

Where COPy = value of COPy for n samples

$\bar{COPy}$ = mean of all COPy values

n = number of samples

For n = 128 (1s), approximate error due to quantisation will be:

Let A = $(COPy - \bar{COPy})^2$

$$\delta A = 2 * (\delta COPy + \delta \bar{COPy})$$

where δCOPy (from section 5.1.1.1) = 0.270mm

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta \bar{COPy} \text{ 1s} = \frac{\sqrt{0.270^2 * 128}}{128} = 0.024 \text{ mm}$$

$$\delta A = 2 * (0.270 + 0.024) = 0.588$$

Let B $= \sum (COPy - \bar{COPy})^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{0.588^2 * 128} \text{ (using quadrature)} = 6.694$$

Let C $= \dfrac{\sum (COPy - \bar{COPy})^2}{n - 1} = \dfrac{B}{n-1}$

$$\delta C = \delta B * \frac{1}{n-1} = 6.694 * \frac{1}{128-1} = 0.052$$

$$\text{COPySD} = \sqrt{\frac{\sum (COPy - \bar{COPy})^2}{n - 1}} = \sqrt{C}$$

$$\delta \text{COPySD} = \frac{1}{2} * \delta C = \frac{1}{2} * 0.052 \qquad \mathbf{= 0.026 \text{ mm}}$$

5.1.4.2 Summary of error and measurement steps in parameters used in this study

Table 5.1.4.1 reports errors for 12-bit and 16-bit ADC data (proofs in Appendix B).

Table 5.1.4.1: Summary of maximum and approximate errors due to quantisation using 12-bit and 16-bit ADC data

		12-bit		16-bit	
Error		max (±)	approx (±)	max (±)	approx (±)
Fx, Fy (N)	range	**0.370**	**0.262**	**0.023**	**0.016**
	SD 1s	**0.373**	**0.018**	**0.023**	**0.001**
	SD 3s	**0.371**	**0.010**	**0.023**	**0.001**
	SD 5s	**0.371**	**0.008**	**0.023**	**0.000**
COPx (mm)	range	**0.486**	**0.344**	**0.030**	**0.022**
	SD 1s	**0.490**	**0.024**	**0.030**	**0.001**
	SD 3s	**0.487**	**0.013**	**0.030**	**0.001**
	SD 5s	**0.487**	**0.010**	**0.030**	**0.001**
COPy (mm)	range	**0.540**	**0.372**	**0.034**	**0.023**
	SD 1s	**0.544**	**0.026**	**0.034**	**0.002**
	SD 3s	**0.541**	**0.015**	**0.034**	**0.001**
	SD 5s	**0.541**	**0.011**	**0.034**	**0.001**
COPAbs (mm)	range	**1.026**	**0.716**	**0.064**	**0.045**
COPxLength	C1 *	**0.486**	**0.344**	**0.030**	**0.022**
(mm)	C2.1 *	**61.722**	**3.877**	**3.858**	**0.242**
	C2.3 *	**186.138**	**6.732**	**11.634**	**0.421**
	C2.5 *	**310.554**	**8.696**	**19.410**	**0.544**
COPyLength	C1 *	**0.540**	**0.372**	**0.034**	**0.023**
(mm)	C2.1 *	**68.58**	**4.192**	**4.287**	**0.262**
	C2.3 *	**206.820**	**7.280**	**12.928**	**0.455**
	C2.5 *	**345.020**	**9.404**	**21.569**	**0.588**
COPAbsLength	C1 *	**1.026**	**0.726**	**0.064**	**0.045**
(mm)	C2.1 *	**129.540**	**8.001**	**8.096**	**0.500**
	C2.3 *	**390.660**	**13.895**	**24.416**	**0.868**
	C2.5 *	**651.780**	**17.948**	**40.736**	**1.122**
COPxSpeed	single	**31.104**	**22.016**	**1.944**	**1.376**
(mm/s)	Ave 1s	**31.104**	**1.946**	**1.944**	**0.122**
	Ave 3s	**31.104**	**1.123**	**1.944**	**0.070**
	Ave 5s	**31.104**	**0.870**	**1.944**	**0.054**
COPxVel	SD 1s	**62.698**	**2.135**	**3.919**	**0.133**
(mm/s)	SD 3s	**62.370**	**1.184**	**3.898**	**0.074**
	SD 5s	**62.305**	**0.906**	**3.894**	**0.057**
COPySpeed	single	**34.560**	**23.808**	**2.160**	**1.488**
(mm/s)	Ave 1s	**34.560**	**2.104**	**2.160**	**0.132**
	Ave 3s	**34.560**	**1.215**	**2.160**	**0.076**
	Ave 5s	**34.560**	**0.941**	**2.160**	**0.059**
COPyVel	SD 1s	**69.664**	**2.308**	**4.354**	**0.144**
(mm/s)	SD 3s	**69.300**	**1.280**	**4.331**	**0.080**
	SD 5s	**69.228**	**0.980**	**4.327**	**0.061**
COPAbsSpeed	single	**65.614**	**45.824**	**4.101**	**2.864**
(mm/s)	Ave 1s	**65.614**	**4.050**	**4.101**	**0.253**
	Ave 3s	**65.614**	**2.338**	**4.101**	**0.146**
	Ave 5s	**65.614**	**1.811**	**4.101**	**0.113**
	SD 1s	**132.261**	**4.443**	**8.267**	**0.278**
	SD 3s	**131.571**	**2.464**	**8.223**	**0.154**
	SD 5s	**131.433**	**1.886**	**8.215**	**0.118**
Tz (Nm)	Range	**1.890**	**1.336**	**0.118**	**0.084**

* Where C1 = case 1 of COP length where the trace is one directional
C2 = case 2 where the COP point is stationary or constantly oscillating
C2.1, C2.3, C2.5 = case 2 for periods of 1s, 3s and 5s.

Table 5.1.4.2 summarises the magnitude of the minimum measurement steps for selected parameters from 12-bit ADC data (proofs in Appendix B). The same process was performed for 16-bit ADC data values and the results have been included. Values have been reported to 3 decimal places for comparison purposes and would not be achievable in either system.

Table 5.1.4.2: Summary of measurement steps for selected parameters using 12-bit and 16-bit ADC data

	12-bit	16-bit
Fx (N)	**0.370**	**0.023**
Fy (N)	**0.370**	**0.023**
COPx (mm)	**0.320**	**0.020**
COPy (mm)	**0.453**	**0.028**
COPx speed/velocity (mm/s)	**20.513**	**1.282**
COPy speed/velocity (mm/s)	**29.038**	**1.815**
COPAbsSpeed (mm/s)	**35.553**	**2.222**

(Fz = 750N was used for all COP measurement step calculations)

Fx and Fy are directly affected by the quantisation error that is generated in the ADC process, as both are measured by the force plate and sampled by the ADC board. Approximate error due to quantisation in Fx and Fy range using 12-bit ADC was calculated to be ±0.262N (table 5.1.4.1). This error is high relative to the mean FxRange and FyRange found in this study of between 0.64N and 1.34N for the rifle group and between 0.67N and 1.67N for the pistol group for all measurement periods. The error due to quantisation lies between 16% and 41% of these mean values. Also, the measurement step of 0.370N (table 5.1.4.2) provides only 2 and 8 steps across which Fx and Fy could be measured in this range of values. In comparison, the measurement step of 0.023N using 16-bit ADC provides between 27 and 72 measurement steps for the same range of Fx and Fy values, while the error of ±0.023N is relatively small (1%-4%). This suggests that measurement of range in Fx and Fy for body sway measurement in elite shooting is not adequately measured using 12-bit ADC and requires 16-bit ADC.

The approximate error due to quantisation in FxSD and FySD using 12-bit ADC ranged from ±0.018N in the 1s period to ±0.008N in the 5s period. These errors are reduced to ±0.001N in the 1s and 3s periods and less than ±0.001N in the 5s period using 16-bit ADC. These results indicate that FxSD and FySD will be largely independent of quantisation error for both 12-bit and 16-bit ADC. However, measurement of standard deviation from data with only 2 to 8 measurement steps provided by 12-bit ADC will certainly hold limitations.

It is of interest that error propagated in standard deviation measures due to quantisation is reduced in the longer periods of measure. This reflects the method of calculating the propagation of error by quadrature summation. However, there will be greater cancelling effect of random errors (such as quantisation error) over a larger sample size. Further, an increase in the number of samples will reduce the relative influence of a single measure on the overall error.

COPx and COPy single measure errors and resolutions were calculated and discussed in sections 5.1.1.1 and 5.1.1.2. Approximate error due to quantisation in the calculation of COP range (±0.344mm for COPx and ±0.372mm in COPy) are high relative to the ranges likely to exist in shooting. Table 5.1.4.3 highlights this error expressed as a percentage, relative to COP range values reported in selected studies. As can be noted, the high percentage error values evident in data obtained from 12-bit ADC (up to 51%) are reduced to less than 3.1% using 16-bit ADC. This indicates that 12-bit ADC data will not be sufficient to accurately measure COP ranges in elite shooters, and this measurement requires 16-bit ADC.

Table 5.1.4.3: Error due to quantisation expressed as a percentage of COP Range values reported in selected studies

Researcher(s)	Discipline	COP Range values (mm)	Percentage error using 12-bit ADC	Percentage error using 16-bit ADC
Mason *et al.* (1990)	Standing pistol shooting	**3.1 - 3.3**	**10%-12%**	**<1%**
This study	Standing pistol shooting	**0.96 - 1.89**	**20%-36%**	**<1%**
Viitasalo *et al.* (1997)	Running target rifle shooting	**1.78 - 2.54**	**13%-21%**	**<1%**
This study	Standing rifle shooting	**0.74 - 3.28**	**10%-51%**	**<3.1%**

Errors calculated using Taylor's (1982) methods for standard deviation parameters indicate that quantisation error will have minimal effect on these measures. The approximate error using 12-bit ADC was calculated to be ±0.024mm in COPxSD and ±0.026mm in COPySD for the 1s period, while these errors were reduced to less than 0.002mm from 16-bit ADC data. Errors from both systems were reasonably small (less than 10%) relative to mean COPxSD and COPySD values for this study lay between 0.21mm and 0.88mm for the rifle group (table 5.2.2.1) and 0.29mm and 1.41mm for the pistol group (table 5.2.2.2) across all sample periods. While this may represent an acceptable error level, SD measures calculated from 12-bit ADC data will be based on COP measured across only 3-13 steps which will impose a limitation on the measure. 16-bit ADC, measuring COP across 47-208 steps will provide more suitable data for SD calculations.

The error due to quantisation in COP length is potentially very large, as detailed in table 5.1.4.1, but depends on the nature of the COP movement. For example, using

12-bit ADC data, the maximum error in COPxLength measured over 5 seconds was calculated as ±0.486mm if the trace moves constantly in one direction. This error could also be as high as ±310.554mm if the COP is stationary or constantly oscillates. However, it is unlikely that the maximum error will ever be realised, as it would require each measurement to be in maximum error and for shooters to be completely stationary, or oscillate at half the sampling frequency (in which case smoothing would eliminate this error due to its high frequency). The approximate error value for this measure using 12-bit ADC data was calculated to be ±8.696mm. This value is still large relative to the mean COPxLength value of 10.81mm for rifle shooters found in this study over 5s (table 5.2.2.1). While smoothing will reduce quantisation error in length measures, the signal is measured with an approximate error of magnitude similar to that of the true signal and as such is questionable.

16-bit ADC data reduces the approximate error due to quantisation in COPxLength in the 5s period error to ±0.544mm, which provides an error relative to the mean rifle group value of 10.81mm of 5.1%. While this may be acceptable, the relative error increases as the sample period decreases. The mean COPxLength over 3s was 6.08 mm, with an approximate error due to quantisation of ±0.421mm (6.9%), while mean COPxLength over 1s was 1.89mm, with an approximate error of ±0.242mm (12.8%). This error may be a limitation of this measure. However, as mentioned, smoothing will reduce it. Further, as was found in spectral analyses reported in Appendix D, body sway exists below 3Hz, with the major amplitude of movement existing below 1Hz. As such, the COP trace will change direction only a few times in the shorter periods of measure. Figure 5.1.4.5 shows an example COP trace for a rifle shooter (over a 1s period). As can be noted from this figure, only four peaks or troughs are evident in the COP trace. Recalling from section 5.1.4.1, the error due to quantisation in the length measure is sensitive to direction changes, with the number of direction changes linked to amount of quantisation error that may exist in the measure. This being the case, error due to quantisation in the data presented in figure 5.1.4.5 will be four (four changes of direction) multiplied by the error of a single COP measure (4 * 0.022mm = 0.088mm). This represents a relative error of less than 1%, which is acceptable in this analysis. Even by this rationale, the relative error using 12-bit ADC data is still large (15%).

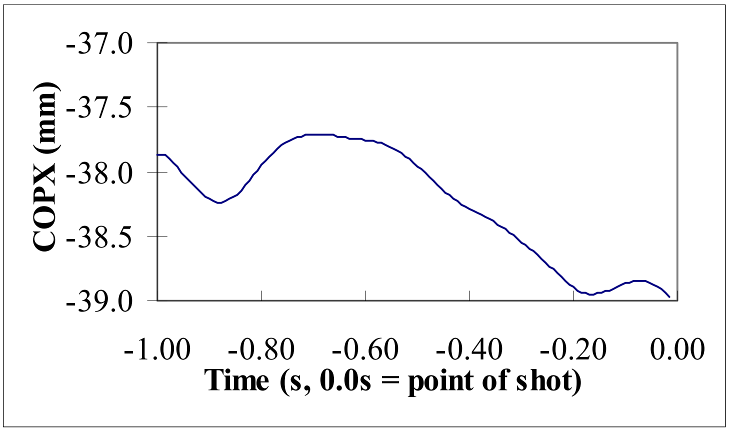


Figure 5.1.4.5: Example COPx curve from a rifle shooting trial.

A significant point to note with length calculations is the error is dependent on the number of samples. An increased sample rate or period will increase the error associated with quantisation, due to the summing effect of the error.

COP speed single measures are unusable for posture sway measurement of shooters when calculated from data obtained by 12-bit ADC. From table 5.1.4.1, the approximate error in a single measure of COPAbsSpeed is ±45.824mm/s, with a maximum possible error of ±65.614mm/s. The approximate measurement steps of COPAbsSpeed are 35.3mm/s (table 5.1.4.2). This precision of measure would be questionable in most COP measurement applications, but totally unsuitable in shooting. 16-bit ADC improves the measurement step of COPAbsSpeed to 2.222mm/s from 35.553mm/s in 12-bit ADC. Using 16-bit ADC, the maximum and approximate errors for a single measure of COPAbsSpeed were reduced to ±4.101mm/s and ±2.864mm/s (table 5.1.4.2). These errors are still quite high relative to values obtained in this study. Mean COPAbsSpeed for rifle shooters at the point of shot was 2.9mm/s (table 5.2.2.1). Both, the minimum measurement step and error values are similar to this value, making use of this parameter inadvisable. This was also the case with COPxSpeed and COPySpeed single measures, with measured values that were similar in magnitude to the error due to quantisation.

The approximate error due to quantisation in average speed measures was considerably reduced from the single measure errors. Using 12-bit ADC, the approximate error in COPAbsSpeed, averaged across the 1s period, was calculated to be ±4.050mm/s compared to a single measure error of ±45.824mm/s. However, this error remained large relative to the values obtained in this study, with rifle shooters averaging 3.133mm/s and pistol shooters averaging 4.224mm/s in the last second prior to shot. Further, speed is still measured in very large steps (35.3mm/s). Quantification of values that may be 8-10 times less than the minimum measurement step are unusable in scientific research.

Errors due to quantisation in COPAbsSpeedAve were reduced using 16-bit ADC to ±0.253mm/s, ±0.146mm/s and ±0.113mm/s for 1s 3s and 5s respectively. These values are well below the mean pistol and rifle group mean values of between 3.133mm/s and 4.615mm/s in this study (tables 5.2.2.1 and 5.2.2.2) indicating that 16-bit data would provide suitable data for this calculation. However, the measurement steps of 1.282mm/s for COPx and 1.815mm/s for COPy are large relative to the mean group values, indicating that these values will be calculated based on only a few measurement steps. As such, the calculation of velocity or speed from COP data sampled using 16-bit ADC still has limitations when measuring for elite shooters.

Due to the large error and measurement step associated with speeds and velocities, 12-bit ADC SD measures also hold the potential to contain a large error due to quantisation. This error is largest relative to the measured values in the 1s period. The approximate error for COPAbsSpeedSD was ±4.443mm/s in the 1s period which is high relative to values obtained for COPAbsSpeedSD of 1.52mm/s for the rifle shooting group and 4.22mm/s for the pistol shooting group (tables 5.2.2.1 and 5.2.2.2). With error of similar value to the measures obtained, standard deviations of speeds are questionable for use in shooting using 12-bit ADC. Further, as mentioned, these speeds and velocities are measured in steps 8-10 times larger than the group means, indicating that any parameter using this data will be unsuitable. Conversely, the effects of quantisation error on COPxVelSD, COPyVelSD and COPAbsSpeedSD are minimal using 16-bit ADC. For example, the approximate error in COPxVelSD for rifle shooters was calculated to be ±0.133mm/s in the 1s period, while the measured value during this time was ±1.994mm/s. This represents a relative error of

6.7%, which is an acceptable level of error, although, obviously, if comparison values lie within 6.7% of each other, comparisons will be possibly compromised in this period. The error was smaller relative to the measured values returned by the rifle group in the 3s (5.5%) and 5s (5.0%) periods. The pistol group returned larger values for all parameters. As such, relative error is lower than the values reported for the rifle group (less than 3%). However, the measurement of speeds and velocities over just a few measurement steps represents a limitation of this measure, even using 16-bit ADC.

It should be noted that both the error due to quantisation and the measurement step of speed and velocity are dependent on the sampling rate. As sampling rate increases, the error due to quantisation and the measurement step increases, as the calculation divides displacement or distance by time. As such, the smaller the time interval between samples, the larger the potential discrepancy between true and measured values. The data that is presented in this study is sampled at 128 Hz and errors and measurement steps that have been calculated are specific to that sample rate.

TzRange showed a maximum error due to quantisation of ±1.89Nm, with an approximate error of ±1.336Nm using 12-bit ADC. As mean rifle group Tz values found in this study (table 5.2.2.1) ranged from 0.12Nm to 0.19Nm. Errors in this measure are considerable, being larger than the measured value. 16-bit ADC improved the maximum error to ±0.118Nm with an approximate error of ±0.084Nm. However, the magnitude of these errors is still similar to the magnitude of the measured values. The very low signal in Tz produced by the rifle shooting group means that the relative error is large. Neither 12-bit ADC nor 16-bit ADC seem suitable for the measurement of TzRange in elite shooters, although, as will be discussed in section 5.2.1, the very low values returned for Tz suggest that it is not important to shooters and its further use is not necessary.

It should be noted that this analysis quantified the error due to quantisation on raw data and on single shots only. As mentioned on numerous occasions, smoothing will reduce the error due to quantisation that occur in the ADC process. Also, averaging across trials and shooters will reduce the error due to quantisation because of cancelling effects. That is, if quantisation is random, the errors in each parameter might be expected to be normally distributed about the true result. Averaging in this study has taken place firstly for a single shooter, with parameters being averaged across a number of shots, then each shooter's data was averaged again to find a group average. However, when comparing body sway and aim point, an individual shot basis is required. As such, error due to quantisation in body sway measures for single shots will influence the analysis.

5.1.5 Experimental assessment of 12-bit and 16-bit ADC

Data collected using a 12-bit ADC and a 16-bit ADC system from three shooting trials and two trials with a 750N weight placed on the force plate were smoothed using a fourth order Butterworth digital filter with a cut-off frequency of 4Hz. Obviously, each smoothed signal will be a combination of sway signal and noise below the 4Hz cut-off, or noise only for the 750N weight trials. This comparison, then, not only contrasts 12 and 16-bit ADC, but different noise experienced in each data acquisition system. Noise below 4Hz may be different between the systems due to different conditions (ie. computer and ADC noise as well as environmental noise picked up by the separate cabling). The signal from the AMTI force plate was passed through the AMTI amplifiers, after which it was split and passed to each computer. Although the computers were located beside each other, separate cables ran to each computer and obviously different ADC boards and computers were used. This limits the practical significance of these results as differences are influenced by the specific data acquisition systems used.

Table 5.1.5.1 shows the average values for selected parameters calculated over 5s for the two trials with the 750N weight on the force plate. The 12-bit ADC system shows slightly larger values for all parameters with the exception of COPy Range. This may be due to the effects of quantisation or of the different levels of noise in the different systems, but is probably a combination of both.

Table 5.1.5.1: Average values for selected parameters calculated from trials with 750N weight placed on the force plate using 12 and 16-bit ADC

Parameter	16-bit ADC	12-bit ADC
COPxLength (mm)	**1.42**	**2.83**
COPxRange (mm)	**0.23**	**0.41**
COPyLength (mm)	**2.41**	**3.07**
COPyRange (mm)	**0.37**	**0.30**
COPAbsSpeedAve (mm/s)	**0.62**	**0.93**
COPAbsSpeedSD (mm/s)	**0.38**	**0.64**

For the purposes of discussion, one shooting trial was chosen to compare 12-bit and 16-bit data.

Figures 5.1.5.1 and 5.1.5.2 present raw COP data for 12 and 16-bit ADC data collection for the selected shooting trial. As can be noted from figure 5.1.5.1, the 12-bit data COP trace has notable measurement steps in its path, and only a vague pattern evident. The 16-bit ADC data, in comparison, is relatively smooth and a path is clear. Visual inspection of the area encompassed by both curves indicates the 12-bit ADC data is slightly larger than the 16-bit data.

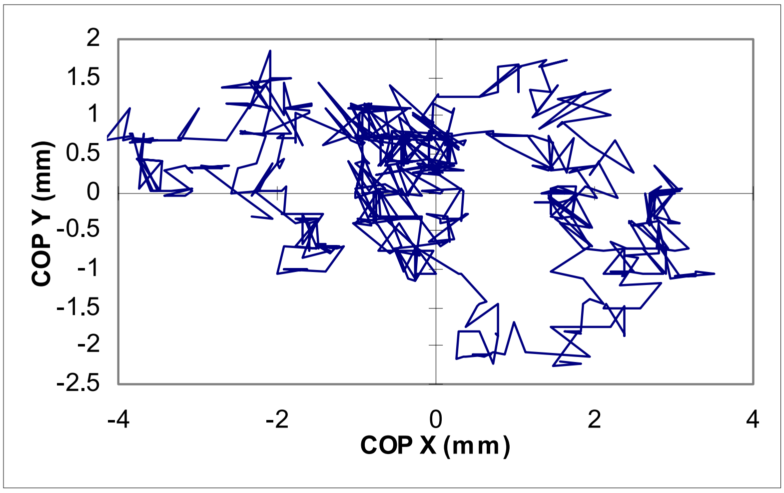


Figure 5.1.5.1: COP trace calculated from raw 12-bit ADC data (pistol shooting trial - subject weight = 980N).

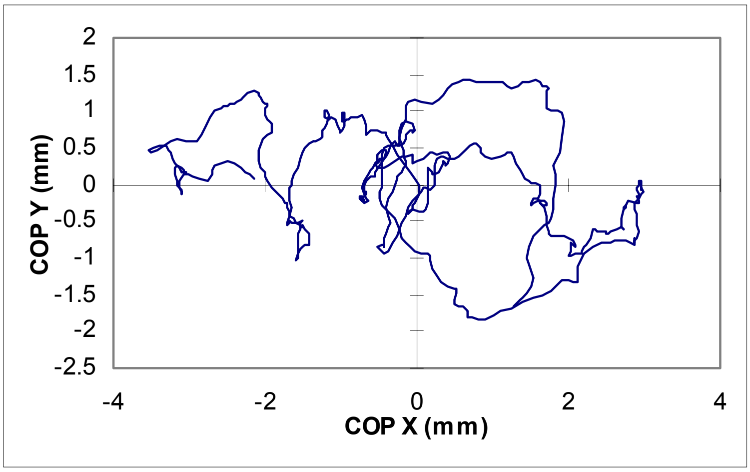


Figure 5.1.5.2: COP trace calculated from raw 16-bit ADC data (pistol shooting trial - subject weight = 980N).

Figures 5.1.5.3 and 5.1.5.4 present the smoothed COP path of the 12-bit and the 16-bit ADC data collection. The smoothed curves are quite similar in overall pattern. The

12-bit data does show slightly larger ranges and a slightly less smooth curve compared to the 16-bit data.

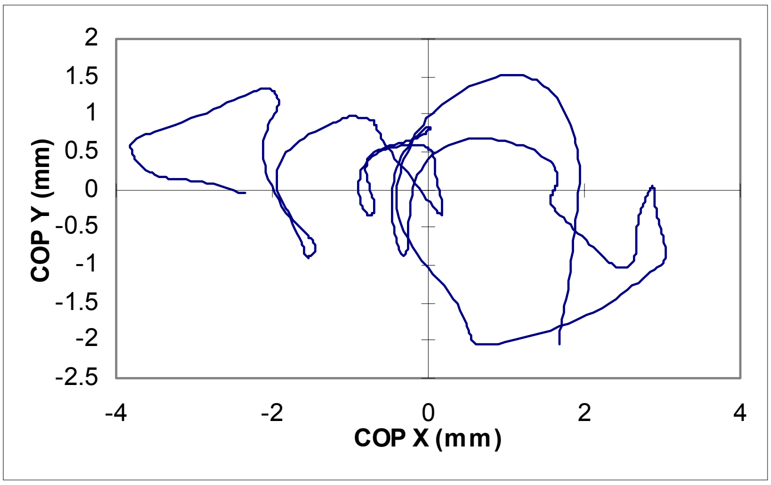


Figure 5.1.5.3: COP path calculated from smoothed 12-bit ADC data (pistol shooting trial).

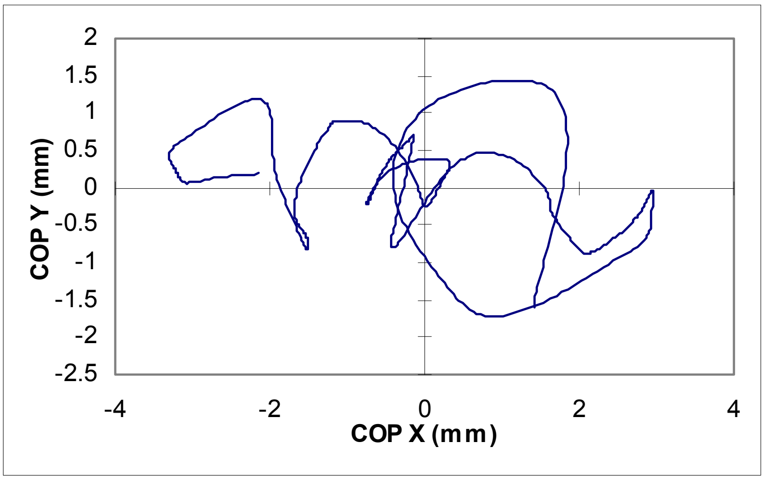


Figure 5.1.5.4: COP path calculated from smoothed 16-bit ADC data (pistol shooting trial).

Figure 5.1.5.5 contrasts COPx displacement curves calculated from 12-bit ADC and 16-bit ADC. Similarly, figure 5.1.5.6 contrasts COPy displacement curves calculated from data using the two systems. In the COPx direction, both curves showed a similar overall pattern and phase. On closer inspection it can be noted that the 12-bit data is slightly larger in range than the 16-bit data. The major divergences occur at the positive and negative peaks of the data. Although it is not possible to discern whether differences are due to noise and quantisation, this is consistent with the limitations of 12-bit compared to 16-bit data capture. While 12-bit ADC may adequately measure the COP during movement in one direction, on changing direction, it will not offer the precision of the 16-bit data. As there are fewer points to describe the COP at the ends of range, the curves can differ more markedly than during movement where a basic path can be traced adequately. This difference is more noticeable in the COPy displacement comparison in figure 5.1.5.6. While the COPy trace, as for the COPx data, showed a similar phase and magnitude of curves for 12 and 16-bit data, the curves varied more about the positive and negative peaks.

Figure 5.1.5.5: COPx displacement for 12 and 16-bit ADC for a shooting trial.

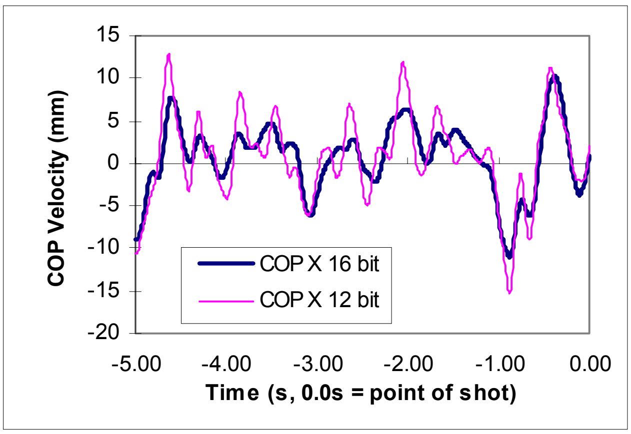


Figure 5.1.5.6: COPy displacement for 12 and 16-bit ADC for a shooting trial.

Figures 5.1.5.7 and 5.1.5.8 show the COPx and COPy velocity curves from the same shooting trial. Both paths were reasonably similar, although there are notable differences at positive and negative peaks.

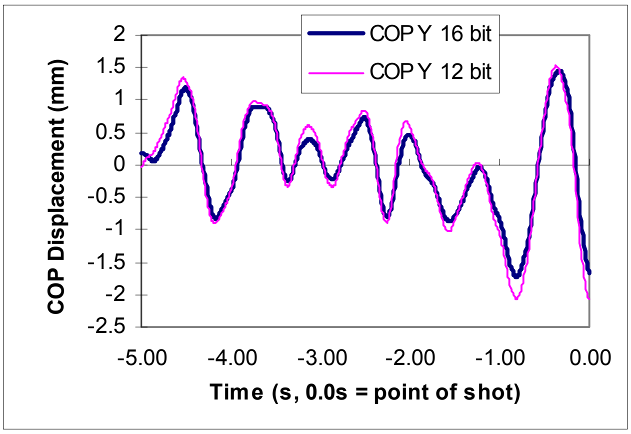


Figure 5.1.5.7: COPx velocity for 12 and 16-bit ADC for a shooting trial (5s).

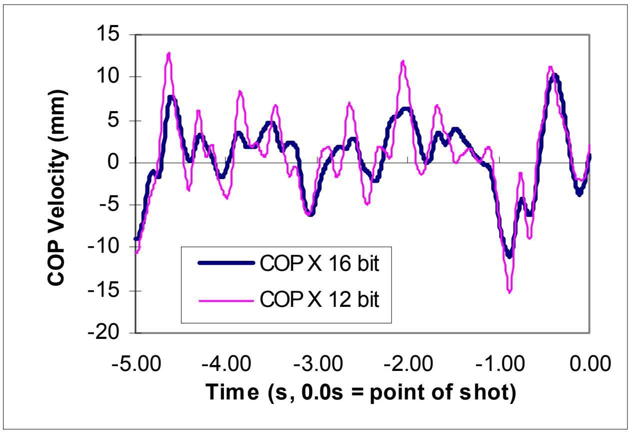


Figure 5.1.5.8: COPy velocity for 12 and 16-bit ADC for a shooting trial (5s).

Table 5.1.5.2 reports selected COP parameters sampled over five seconds from 12 and 16-bit ADC data sampled simultaneously for one pistol shooter. All parameters were higher than the group averages (discussed in section 5.2.1) and COP ranges found by Mason *et al.* (1990), although the Mason *et al.* data was sampled for only 1s. The shooter had been out of training for a period which may have adversely affected performance, although it was felt that each trial was typical of competition and scores on target were all above nine.

Table 5.1.5.2: Average values for selected COP parameters calculated from three pistol shooting trials using 12-bit and 16-bit ADC

Parameter	16-bit ADC	12-bit ADC
COPxLength (mm)	**15.68**	**16.86**
COPxRange (mm)	**4.43**	**4.81**
COPyLength (mm)	**17.23**	**19.05**
COPyRange (mm)	**2.62**	**2.88**
COPAbsSpeedAve (mm/s)	**5.17**	**5.67**
COPAbsSpeedSD (mm/s)	**2.87**	**3.24**

In all cases, COP parameters calculated from 12-bit ADC data returned larger values than the corresponding measure calculated from 16-bit ADC data. 12-bit ADC parameters were, on average, 9.8% larger than the 16-bit ADC parameters. Obviously in this comparison, if quantisation error was the only contributing factor, 12-bit ADC values might be expected to vary higher or lower than 16-bit ADC values, as this error may overestimate or underestimate values. This was noted in two of the individual shot trials, where COPy ranges were shown to be smaller for 12-bit ADC compared to 16-bit ADC. However, it can only be concluded that these systems measured slightly different values for the same activity.

While differences between 12-bit and 16-bit ADC data were evident, these differences were not as large as expected. However, these results may have been affected by the COP values produced by the shooter tested. As mentioned previously, the range values were above the pistol group average (reported in section 5.2.1). This would have decreased the relative influence of 12-bit compared with 16-bit data collection. Further, the shooter was one of the heavier shooters tested (1090N). As shown earlier, the effects of quantisation are reduced and COP is measured with greater resolution as

Fz is increased. Lighter shooters or smaller COP ranges may show a more significant difference between 12 and 16-bit ADC.

Overall, test data indicated that 12-bit and 16-bit data will obtain slightly different data when smoothed using a 4Hz digital filter. This experimental comparison of 12-bit and 16-bit ADC data capture is limited as noise will differ between systems and characteristics of each DC board will influence the data. It cannot be concluded, then, if the difference between the systems was due to quantisation error or due to noise differences and is probably a combination of both. However, as discussed, quantisation error can contribute to error, particularly at the range limits of COP movement, and this error will be larger in 12-bit ADC data. A fluctuation of one ADC step in the 12-bit system will be 16 times larger than one ADC step in the 16-bit system. As such, if each system were to fluctuate by one or two steps, both systems will register an error. However, the 12-bit system will return raw data errors that are approximately 16 times larger than the errors produced by the 16-bit data. Smoothing will reduce these errors, but will not necessarily eliminate them.

5.2 Stage 2

Labeling of tables and figures has been presented to three levels (plus table number) in 5.2.1 and 5.2.1 (eg. table 5.2.1.1), and four levels for sections 5.2.2.1, 5.2.2.2, 5.2.3.1 and 5.2.3.2 (eg. table 5.2.3.1.1).

5.2.1 Body Sway Parameters

At the completion of data collection, all body sway parameters were quantified for each shooter (this data, along with shooting performance and aim point parameter values, is included in Appendix C). Means were calculated for each body sway parameter for the rifle-shooting group and the pistol-shooting group. Results are presented in the next sections. This data was then examined to establish the minimum number of parameters that would adequately describe body sway in this study. For the reader's reference, this section presents all body sway data with a brief discussion and example curves. The major discussion of body sway parameters (or those chosen for further analysis from this section) along with shooting performance and aim point fluctuation is presented in sections 5.2.2 and 5.2.3.

5.2.1.1 Rifle Shooters

Table 5.2.1.1 details the average values for body sway parameters across 5s, 3s and 1s prior to shot (N=6).

Table 5.2.1.1: Mean body sway values for the rifle-shooting group (N=6)

		5s		3s		1s	
		Mean	*SD*	Mean	*SD*	Mean	*SD*
FxRange	N	**1.38**	***0.41***	**1.12**	***0.30***	**0.71**	***0.20***
FxSD	N	**0.30**	***0.09***	**0.26**	***0.08***	**0.20**	***0.06***
FyRange	N	**0.99**	***0.23***	**0.88**	***0.20***	**0.64**	***0.13***
FySD	N	**0.21**	***0.05***	**0.20**	***0.05***	**0.18**	***0.04***
COPxLength	mm	**10.81**	***2.59***	**6.03**	***1.29***	**1.81**	***0.41***
COPxRange	mm	**3.28**	***0.82***	**2.29**	***0.49***	**1.08**	***0.27***
COPxSD	mm	**0.88**	***0.22***	**0.65**	***0.16***	**0.32**	***0.08***
COPyLength	mm	**11.62**	***3.45***	**6.88**	***2.03***	**2.16**	***0.60***
COPyRange	mm	**1.23**	***0.35***	**1.06**	***0.31***	**0.74**	***0.21***
COPySD	mm	**0.27**	***0.08***	**0.25**	***0.08***	**0.21**	***0.06***
COPAbsLength	mm	**17.77**	***3.93***	**10.19**	***2.18***	**3.13**	***0.65***
COPAbsRange	mm	**3.47**	***0.86***	**2.51**	***0.56***	**1.32**	***0.29***
COPxVelSD	mm/s	**2.68**	***0.64***	**2.43**	***0.52***	**1.99**	***0.45***
COPyVelSD	mm/s	**2.89**	***0.84***	**2.83**	***0.82***	**2.58**	***0.71***
COPAbsSpeedAve	mm/s	**3.55**	***0.79***	**3.40**	***0.73***	**3.13**	***0.65***
COPAbsSpeedSD	mm/s	**1.88**	***0.41***	**1.77**	***0.37***	**1.52**	***0.34***
TzRange	Nm	**0.19**	***0.02***	**0.16**	***0.03***	**0.12**	***0.03***
At Shot							
COPxSpeed	mm/s	**1.67**	***0.59***				
COPySpeed	mm/s	**1.92**	***0.53***				
COPAbsSpeed	mm/s	**2.91**	***0.54***				
Tz	Nm	**-5.23**	***3.05***				

Over 5s, the mean FxRange was only 1.38N while the mean FyRange was only 0.99N. Values were smaller for the 3s and 1s time period. It should be noted that, as the measurement periods overlap, range measures will always be equal to or less than the longer measurement period range. As such, it is inappropriate to compare time periods. No comparison data exists in the literature for horizontal force ranges. In the 5s period, FxSD (0.30N) and FySD (0.21N) were smaller than 0.71N in the AP direction (approximately equal to the FxSD in this study) and 0.85N in the ML direction (approximately equal to the FySD in this study) reported by Goldie *et al.* (1989). The subjects used by Goldie *et al.* were non-shooters and would be expected to produce more horizontal force than shooters, although direct comparison is inappropriate as the sample periods were considerably different (32s in the Goldie *et al.* study).

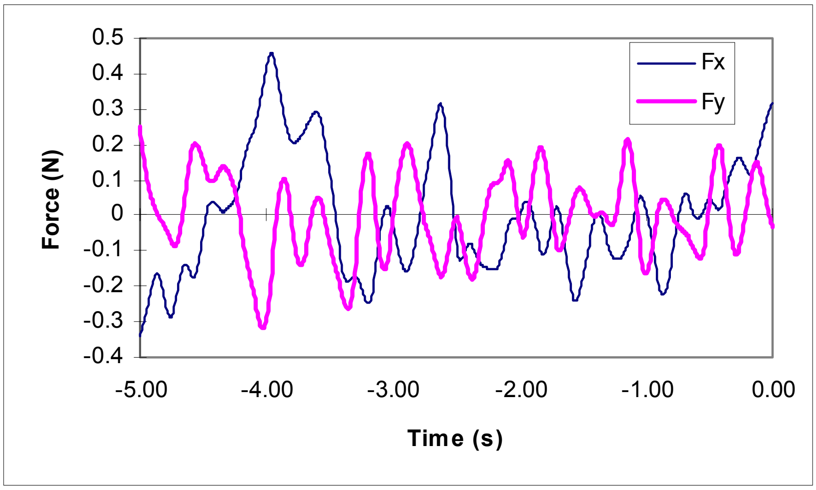


Figure 5.2.1.1: Example Fx and Fy curve over 5s from a rifle-shooting trial.

Values were greater in COPxRange compared with COPyRange for 5s, 3s and 1s (table 5.2.1.1), indicating more movement was produced by the rifle-shooting group perpendicular to rather than parallel to the line of shot, as can be noted in the example COP displacement curve in figure 5.2.1.2. Mean group ranges in the 3s period were 2.29mm and 1.06mm for COPxRange and COPyRange respectively, which were similar to the COP ranges found in running target rifle shooters by Viitasalo *et al.* (1997) of 1.92mm - 2.54mm for COPx measured over variable periods of 2s to 4s.

This will be discussed further in the analysis of rifle and pistol shooting (sections 5.2.2 and 5.2.3). No comparison data exists for SD measures in rifle shooting. However, COPxSD (0.32mm) and COPySD (0.21mm) returned smaller values than those reported by Mason and Pelgrim (1989) from archers in the last second before shot of 0.49mm and 0.52mm for COPx and COPy respectively.

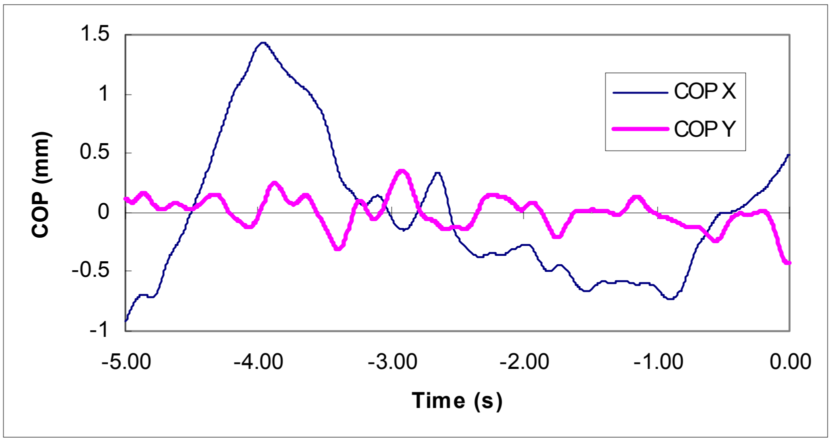


Figure 5.2.1.2: Example COPx and COPy displacement curves over 5s from a rifle-shooting trial.

Mean COPxLengths for the rifle-shooting group were 10.81mm, 6.03mm and 1.81mm over 5s, 3s and 1s respectively. Interestingly, these values are smaller than COPyLength values of 11.62mm, 6.88mm and 2.16mm for the same measurement periods. This will be discussed in section 5.2.2 and 5.2.3.

COPxVelSD and COPyVelSD values ranged from 2.89mm/s to 1.99mm/s. As for length and force measures, values were greater in the Y-axis compared with the X-axis. No data exists in the literature for comparison. As can be noted from figure 5.2.1.3, while ranges of COPx velocity and COPy velocity were similar, COPy velocity fluctuates more than COPx velocity, as indicated by more frequent crossing of the zero velocity line. This further indicates a different mechanism of control between X and Y-axis movement. As mentioned, this will be discussed in section 5.2.2 and 5.2.3.

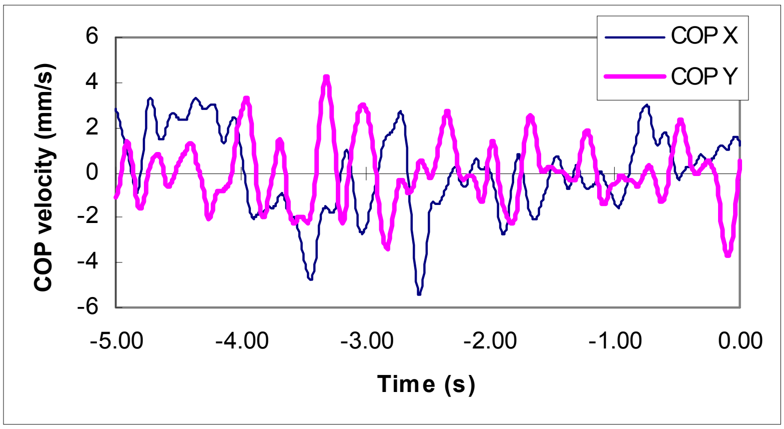


Figure 5.2.1.3: Example COPx and COPy velocity curves over 5s from a rifle-shooting trial.

COPAbsSpeedAve returned values of 3.55mm/s, 3.40mm/s and 3.13mm/s for the 5s, 3s and 1s period respectively. These values are considerably smaller than those reported by Ekdahl *et al.* (1989) who found COP speeds of between 13 mm/s and 14mm/s for non-shooters, although, as mentioned, non-shooters would be expected to sway more than shooters. COPAbsSpeedSD returned values of 1.88mm/s, 1.77mm/s and 1.52mm/s for the 5s, 3s and 1s period respectively. No comparison data exists in the literature for this parameter. Figure 5.2.1.4 shows an example of COPAbsSpeed in the 5s prior to shot.

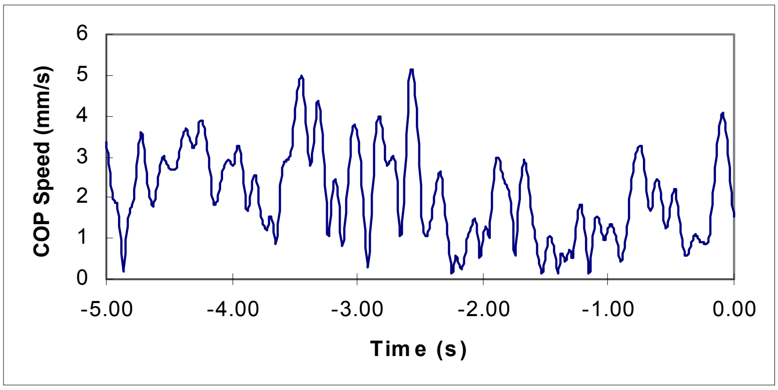


Figure 5.2.1.4: Example COPAbsSpeed curve over 5s from a rifle-shooting trial.

Figure 5.2.1.5 shows the Tz curve over 5s for a rifle-shooting trial. The range of fluctuations tends to reduce as the point of shot (0.00s) approaches. Also noticeable is the very small amount of signal present in Tz. Mean TzRanges of 0.12Nm to 0.19Nm were found for the rifle-shooting group across the three measurement periods (table 5.2.1.1), indicating that there is minimal signal in Tz. There is no comparison data in the literature.

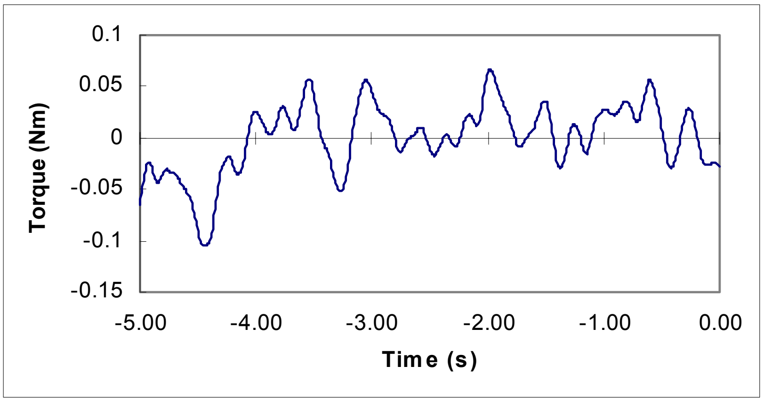


Figure 5.2.1.5: Example Tz curve over 5s from a rifle-shooting trial.

5.2.1.2 Pistol Shooters

On completion of quantification of data for the pistol-shooting group, it was noticed that mean Aim Time, defined as the length of time between the aim point first intersecting the target to the point of shot, was only 4.22 seconds. This short aim time affected the proposed study. 5s, 3s and 1s periods were to be examined. Examination of individual shots showed that aim times ranged from 1.5s to 11s, with no shooters returning aim times over 3s for all shots. It was felt that body sway data may be unreliable in the 5s and 3s periods, as the gun was not aligned with the target during these times for some shots. As such, relatively large gun movements could be expected which would have a direct bearing on body sway parameters. On examination of the video of each pistol shooter's testing session, it was noted that many of the shooters were still lowering the gun in the period of 5s before shot. Based on the short and variable aim time and the effects this may have on body sway data, it was decided to limit the pistol-shooting analysis to the 1s period only.

Table 5.2.1.2 details the average values for body sway parameters in the 1s prior to shot (N=5) for the pistol-shooting group.

Table 5.2.1.2: Mean body sway values for the pistol-shooting group (N=5)

		1s	
		Mean	*SD*
FxRange	N	**0.87**	***0.36***
FxSD	N	**0.25**	***0.10***
FyRange	N	**0.67**	***0.18***
FySD	N	**0.20**	***0.05***
COPxLength	mm	**3.01**	***1.03***
COPxRange	mm	**1.89**	***0.34***
COPxSD	mm	**0.58**	***0.10***
COPyLength	mm	**2.33**	***0.53***
COPyRange	mm	**0.96**	***0.20***
COPySD	mm	**0.29**	***0.06***
COPAbsLength	mm	**4.22**	***1.13***
COPAbsRange	mm	**2.17**	***0.33***
COPxVelSD	mm/s	**3.21**	***1.36***
COPyVelSD	mm/s	**2.75**	***0.62***
COPAbsSpeedAve	mm/s	**4.22**	***1.14***
COPAbsSpeedSD	mm/s	**1.92**	***0.55***
TzRange	Nm	**0.14**	***0.03***
At Shot			
COPxSpeed	mm/s	**3.34**	***1.29***
COPySpeed	mm/s	**2.52**	***0.42***
COPAbsSpeed	mm/s	**4.25**	***1.47***
Tz	Nm	**-4.33**	***3.88***

All mean body sway values from the pistol-shooting group were larger than the corresponding values for the rifle-shooting group. This indicates that rifle shooters are more stable than pistol shooters. This will be discussed in section 5.2.3.

The mean group value for FxRange was 0.87N while FyRange showed a slightly smaller range of 0.67N. This slight range difference is evident in figure 5.2.1.6.

While no comparison data exists in the literature for horizontal force range for pistol shooters, mean values of 0.25N in FxSD and 0.20N in FySD were smaller than 0.69N and 0.76N for AP and ML directions respectively reported by Goldie *et al.* (1989). As for the rifle-shooting group, the pistol-shooting group also showed more deviation in Fx compared with Fy.

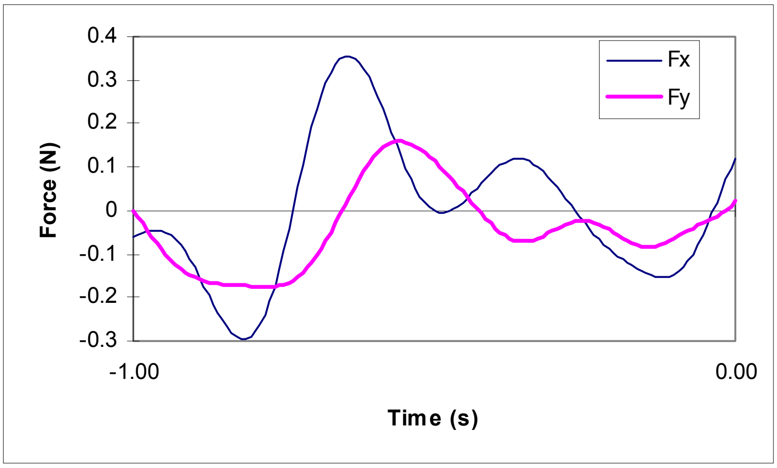


Figure 5.2.1.6: Example Fx and Fy curve over 1s from a pistol-shooting trial.

COPxRange (2.44mm) and COPyRange (1.22mm) were slightly smaller than the ranges found in elite pistol shooters by Mason *et al.* (1990) of 3.1mm and 3.3mm for COPxRange and COPyRange respectively. As for the rifle-shooting group, there was greater range in COPx than COPy over 1s, indicating more movement perpendicular to rather than parallel to the line of shot, as can be noted in figure 5.2.1.7. COPxSD was also larger than COPySD. COPxSD returned a value of 0.58mm, while COPySD returned 0.29mm which were similar to values recorded from archers in the last second before shot of 0.49mm and 0.52mm for COPx and COPy respectively (Mason and Pelgrim, 1989). As for the rifle-shooting group, the pistol-shooting group showed more deviation in COPx compared to COPy, which is the opposite of the Mason and Pelgrim finding.

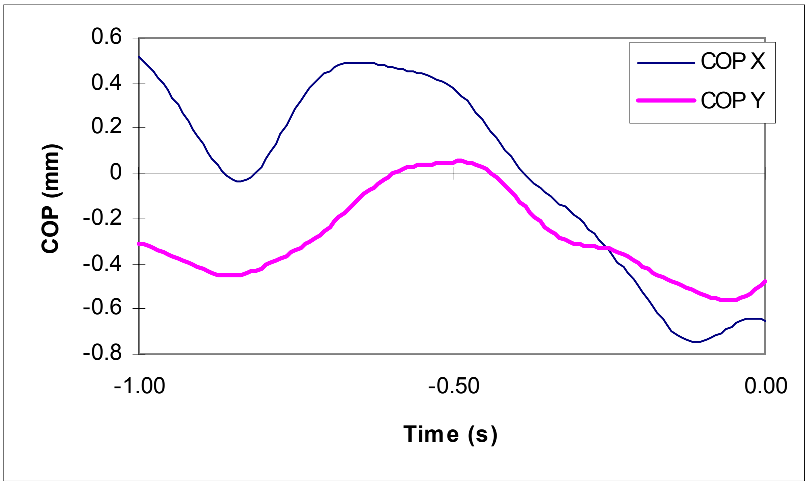


Figure 5.2.1.7: Example COPx and COPy curves over 1s from a pistol-shooting trial.

Mean COPxLength (3.01mm) was larger than COPyLength (2.32mm) for the pistol-shooting group. This differed from the rifle shooters, who showed greater lengths in COPy than COPx. This will be discussed in section 5.2.3.

COPxVelSD and COPyVelSD returned values of 3.21mm/s and 2.75mm/s respectively. The pistol-shooting group returned a larger COPxVelSD value compared to COPyVelSD. This was the opposite of the rifle-shooting group, which returned larger COPyVelSD values. Figure 5.2.1.8 shows an example of COPx and COPy velocity curves over the 1s prior to shot for a randomly selected pistol trial from which COPxVelSD and COPyVelSD were calculated. Evident in this figure is the larger range of velocities produced in COPx, which contributed to the larger COPxVelSD values.

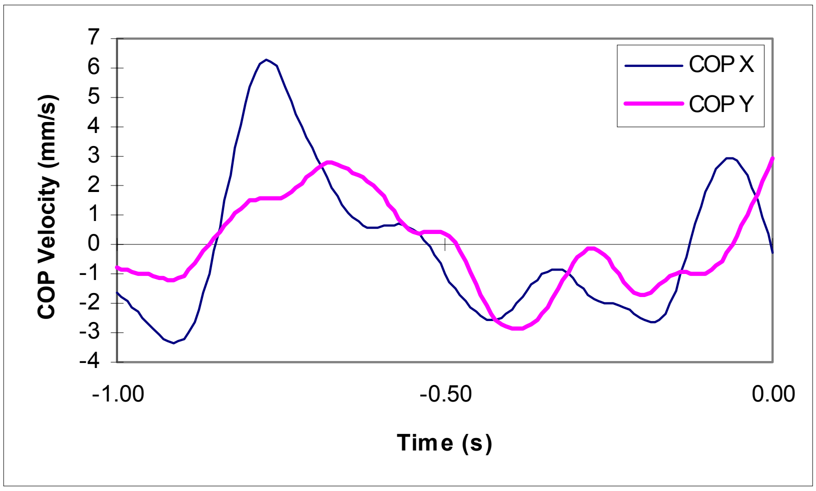


Figure 5.2.1.8: Example COPx and COPy velocity curves over 1s from a pistol-shooting trial.

COPAbsSpeedAve returned a value of 4.22mm/s. This is much smaller than the 13mm/s found by Ekdahl *et al.* (1989) for non-shooters, although, as mentioned earlier, non-shooters would be expected to sway more than shooters.

COPAbsSpeedSD returned 1.92mm/s. No comparison data exists in the literature for this parameter. Figure 5.2.1.9 shows an example of the COPAbsSpeed curve for a pistol-shooting trial, from which these parameters were calculated.

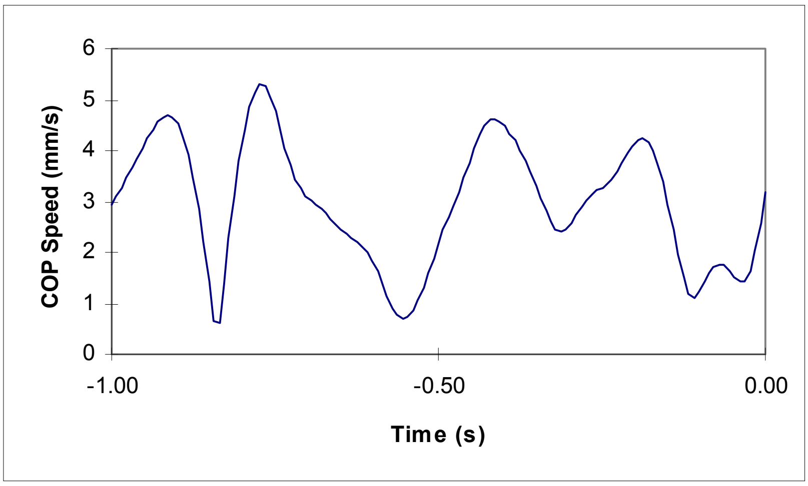


Figure 5.2.1.9: Example COPAbsSpeed curve over 1s from a pistol-shooting trial.

The mean pistol group Tz range value in the 1s period was only 0.14Nm. This value was slightly higher than the rifle-shooting group. As for the rifle-shooting group, pistol shooters produced very little signal in Tz in the 1s period. Figure 5.2.1.10 shows an example of the Tz curve produced by a pistol shooter in the 1s period prior to shot, showing a range of only approximately 0.1Nm.

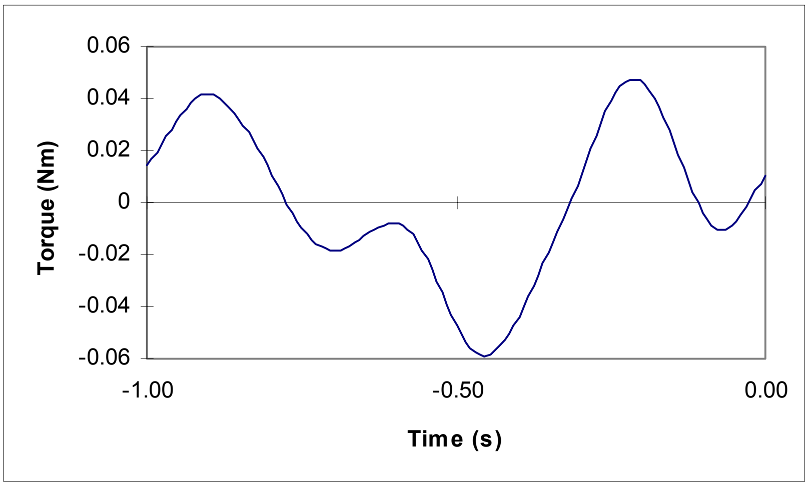


Figure 5.2.1.10: Example Tz curve over 1s from a pistol-shooting trial.

5.2.1.3 Reduction of body sway parameters

Tz was eliminated prior to statistical analysis based on the indistinguishably small signal obtained during testing. Mz, the major contributing channel to the numerator in the Tz calculation exhibited very small levels of signal. The measure indicated that shooters generate little torque about the Z-axis during shooting and, as such, Tz will hold little interest. Further, TzRange values calculated from shooting trials were similar to the values obtained in weighted force plate trials, as can be noted in figure 5.2.1.11. This suggested that the signal in Tz in largely generated by noise, and was not generated by shooters. This further confirmed that minimal body sway signal existed in Tz.

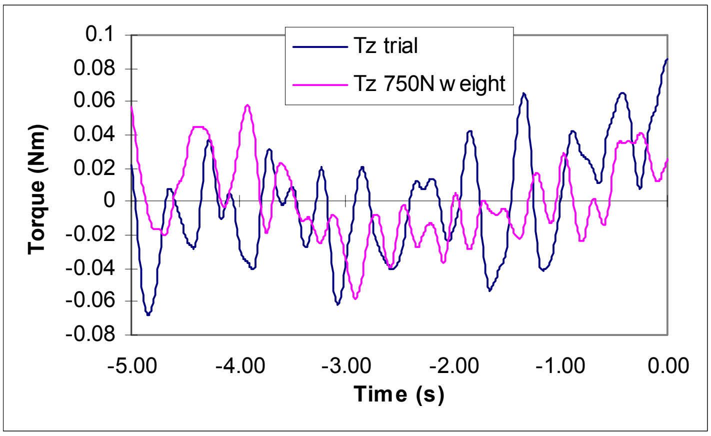


Figure 5.2.1.11: Comparison of Tz curve from a rifle-shooting trial and a trial with a 750N weight placed on the force plate (from smoothed force plate data).

Due to the potential errors and resolution problems detailed in stage 1, all single measure data (ie parameters at the instant of shot) were eliminated from further analysis. Recalling from section 4.2.5, COP speed measures and Tz were to be examined at the point of shot. Tz was eliminated previously. As can be noted from table 5.2.1.3, both the minimum measurement step and approximate error due to quantisation in COP speed measures are of similar magnitude to the values obtained for the rifle and pistol shooting groups. For example, COPx speed of 1.67mm/s for the rifle-shooting group was measured in approximate steps of 1.282mm/s and contained a potential error of ±1.376mm/s. As such these parameters were eliminated from the study due to the potential error problems and poor measurement resolution relative to the measured values for these parameters.

Table 5.2.1.3: Error and measurement step for speed measures and mean values of COP speed at the point of shot for the rifle and pistol shooting group

			Mean value at point of shot	
	Error	Measurement	Rifle-shooting	Pistol-shooting

	(±mm/s)	Step (mm/s)	group (mm/s)	group (mm/s)
COPxSpeed	1.376	1.282	1.67	3.34
COPySpeed	1.488	1.815	1.92	2.52
COPAbsSpee	2.864	2.222	2.91	4.25

5.2.1.3.1 PCA and cross correlations of body sway parameters in the rifle-shooting group

To establish the number of parameters required to assess body sway in this study, and to assess which of these measures were most appropriate for the task, a combination of statistical and theoretical analysis was performed on the quantified body sway parameters. Statistical analysis involved the use of principal components analysis (PCA) to establish the number of factors identified by the 16 remaining body sway parameters. This number of factors relates to the number of parameters required to assess body sway in this study, as all similar parameters are grouped within these factors. Cross correlation analysis was used in conjunction with PCA to find how closely related parameters were for this study. This analysis was performed on body sway parameters calculated from data from the rifle group and individual shooters (5s, 3s and 1s) and the pistol group and individual pistol shooters (1s).

PCA was performed using SPSS version 6.0 to provide an indication of the number of body sway factors being measured by the 16 body sway variables. Initially, Kaiser's measure of sampling adequacy (KMO) was calculated for each data set, with sets returning a KMO value of less than 0.6 being discarded. For each of the analyses, factors with eigen values greater than 1 were considered reliable and were included in

Results. Scree plots were also viewed for each analysis as a check on this criterion. Varimax rotation was performed on the data to aid with the identification of variables associated with particular factors. A loading value, which is the r value for the correlation between the variable and the factor, of 0.56 (p=0.01) was set for variables to be considered as contributing to that factor. Comrey (1973), as reported by Tabachnick and Fidell (1989), suggests that a loading in excess of 0.56 was good. Further, this loading value made interpretation of factors clear. Stevens (1992) suggests that N should be considered when assessing the level of association of a variable with a factor, suggesting that an r value that is double the r value associated with an alpha value of 0.01 is reliable. Unfortunately both authors are considering N> 50 or more. As this study has data with N=5 (pistol), N=6 (rifle) and N=20 (number of shots for an individual), the suggestions of each author cannot be applied stringently. Due to the small number of subjects and trials, this analysis was used only as a guide and, combined with the cross correlation and theoretical analysis, served to identify the minimal number of body sway variables that should be used. The following analysis has been presented in order of PCA followed by cross correlations, with the results of these analyses combined with theoretical analysis of the body sway parameters at the end of this section, where the decision on which body sway parameters used is presented.

KMO values calculated prior the rifle and pistol group data sets were all below 0.6 and excluded from the PCA. As such, PCA was performed only on each individual shooter. Results for all successful individual analyses are included in Appendix E.

18 sets of rifle-shooting data were analysed using PCA (6 shooters times 3 measurement periods), with 14 successful analyses (KMO>0.6) being returned. Of these, eight exhibited three factors in body sway data and four exhibited two factors. This indicated initially that only two to three parameters would adequately describe body sway for rifle shooters in the individual analysis component of this study. For the pistol shooting group (5 shooters times 1 measurement period), two data sets returned two factors, while three data sets returned three factors. The factor loadings for both the rifle-shooting and pistol-shooting groups were similar, with the same parameters aligning within the same factors. In all cases, the deviation accounted for by these factors exceeded 88%. As such, it was decided to use the same body sway parameters for both disciplines. For discussion purposes, only rifle-shooting statistical analyses are presented, with all PCA presented in Appendix E. The selection of parameters to be used in this study is summarised at the end of this section.

Table 5.2.1.4 shows an example of a 2 factor PCA for body sway data measured over 5s (rifle shooter number 3, or R3). As can be noted from this table, all X-axis measures aligned with factor 1, as indicated by the high correlation coefficients, or loadings, with this factor (denoted by bold numbers in table 5.2.1.4). Similarly, all Y-axis measures showed high loading values for factor 2.

Table 5.2.1.4: 2 factor loading matrix for R3 from PCA (N=20 shots, loadings greater than r=0.56, p<0.01, in bold type)

	Factor 1	Factor 2
Range Fx	**0.89**	0.15
SD Fx	**0.91**	0.24
Range Fy	-0.05	**0.89**
SD Fy	0.14	**0.98**

COPxLength	**0.95**	0.18
COPxRange	**0.92**	-0.13
COPxSD	**0.89**	-0.07
COPyLength	-0.02	**0.97**
COPyRange	0.56	**0.57**
COPySD	0.34	**0.88**
COPAbsLength	**0.72**	**0.66**
COPAbsRange	**0.92**	-0.07
COPxVelSD	**0.95**	0.16
COPyVelSD	-0.04	**0.97**
COPAbsSpeedAve	**0.72**	**0.66**
COPAbsSpeedSD	**0.86**	0.42

Absolute measures aligned with one or both factors, as might be expected, given that the X and Y-axis measures are simply the components of these measures. COPAbsRange showed a high loading with Factor 1 and a very low loading with Factor 2. This was also the case with COPAbsSpeedSD, although the loading with factor 2 was larger. This indicates that X-axis measures influenced this parameter considerably more than Y-axis measures. Conversely, COPAbsLength and COPAbsSpeedAve were significantly loaded with both Factor 1 and Factor 2. This indicates a contribution from both X and Y axes to these values. Regardless, COPAbs parameters did not form a factor independent of the component measures in the X and Y axes.

The underlying mechanism that is identified by factor 1 is sway in the X axis, while factor 2 identifies sway in the Y axis. As such, two body sway measures, one from each factor, would adequately describe body sway for this dataset (body sway in the 5s period for R3). A similar loading pattern, with a division of X-axis and Y-axis measures, and with absolute measures showing high loadings with one or both factors, was consistent for all data sets which returned 2 factors (see Appendix E). As such, the same two body sway measures will describe body sway for all 2 factor data sets in this study.

Table 5.2.1.5 shows an example of a 3 factor loading for body sway data (R4) measured over 5s (other results in Appendix E). As for the 2 factor PCA, all Y-axis measures returned high loadings for one factor, with sway in the Y-axis being the mechanism underlying this factor. However, X-axis body sway measures were split between two factors. Factor 2 in table 5.2.1.5 shows high loadings for COPAbsLength, COPAbsSpeedAve, COPxLength, COPxVelSD, and Fx measures, while low loadings were returned for COPAbsRange, COPxRange and COPxSD. As force measures, velocities and length measures were included in this factor, the underlying mechanism seems to be the rate of sway. Factor 3 shows the reverse, with high loadings for COPAbsRange, COPxRange and COPxSD, and low loadings for the remaining X-axis measures. The underlying mechanism identified by this factor would seem to be the amplitude of sway in the X-axis. This indicated that three parameters, one Y-axis and two X-axis measures were required to adequately describe body sway in the 5s period for R4. Of the X-axis measures, one parameter selected from those parameters that were loaded highly for factor 2 and one parameter selected from those parameters loaded highly for factor 3 would be required. This loading pattern was consistent for all data sets that returned 3 factor results, with the exception of one, which will be discussed later. As such, two measures from those used in this study are required to adequately describe body sway in the X-axis, while one parameter is required for the Y-axis for shooters in this study.

Table 5.2.1.5: 3 factor loading matrix for R4 from PCA

(N=20 shots, loadings greater than r=0.56, p<0.01, in bold type)

	Factor 1	Factor 2	Factor 3
FxRange	0.33	**0.85**	0.21
FxSD	0.17	**0.91**	0.31
FyRange	**0.87**	0.34	-0.13
FySD	**0.91**	0.33	-0.14
COPxLength	0.26	**0.91**	0.29
COPxRange	0.02	0.38	**0.92**
COPxSD	-0.09	0.14	**0.95**
COPyLength	**0.94**	0.20	-0.07
COPyRange	**0.86**	0.19	0.27
COPySD	**0.90**	0.20	0.14
COPAbsLength	**0.65**	**0.71**	0.18
COPAbsRange	0.09	0.38	**0.91**
COPxVelSD	0.31	**0.90**	0.30
COPyVelSD	**0.96**	0.17	-0.08
COPAbsSpeedAve	**0.65**	**0.71**	0.18
COPAbsSpeedSD	**0.66**	0.50	0.25

As for the 2-factor analysis, absolute measures did not form a factor independent of the component X and Y measures in any of the analyses that returned three factors from the PCA. This indicated that absolute measures offered no more information than that provided by the component measures in the X and Y axes in this study.

Of the parameters in factor 2 (table 5.2.1.5), COPxLength and COPxVelSD measures showed a strong relatedness in both PCA and cross correlations. This is not surprising, of course, as velocity/speed is linked with length data by a constant, being the time interval between measures. Fx measures were also closely associated with COP length and speed measures, as evident in PCA and cross correlations. Winter *et al.* reports finding that the horizontal acceleration of the CG is proportional to the COP in both AP and ML directions. This being the case, correlations between COP length/speed measures and force measures are not surprising. However, the correlations between ML CG movement and ML COP movement were negative. In this study, Fy values correlated positively with COP movement. Briefly, this was due to the quantities (range and SD) being scalar. As such, range and SD values will provide the same value whether the signal in or out of phase.

Cross correlation analysis of body sway measures performed on the group data supported the PCA results of individual shooters, showing high degrees of relatedness between measures in the same axis. For clarity of presentation, two correlation matrices have been presented for X-axis measures and one for Y-axis measures. These measures have been further divided into the two groups of measures found in the 3-factor PCA result.

Table 5.2.1.6 shows the cross correlation matrix for X-axis and absolute measures that were loaded highly in the same factor in the 5s period; namely COPxRange, COPxSD and COPAbsRange. As can be noted, all measures were strongly correlated. This supports findings from the PCA of individuals and indicates that one of these measures will be sufficient to describe this aspect of body sway in this study.

Table 5.2.1.6: Correlation matrix: X-axis body sway measures from one factor for the rifle-shooting group (N=6, bold type indicates significant at p<0.05)

	COPxRange	COPxSD
COPxSD	**0.99**	
COPAbsRange	**0.98**	**0.99**

Table 5.2.1.7 shows the cross correlation matrix for X-axis and absolute measures that were loaded highly in the same factor in the 5s period; namely Fx measures, COPxLength, COPxVelSD and COPAbsSpeed measures. High coefficients were

returned for all correlations between X-axis measures. Those that were not significant at $p<0.05$ still held a moderately high r value. Fx measures and COPxLength returned coefficients of $r=0.98$, indicating a very strong relationship between these measures. Fx measures also correlated highly with COPxVelSD ($r=0.98$ for both). COPxLength and COPxVelSD were perfectly correlated ($r=1.00$). This confirmed that one measure selected from these parameters would sufficiently describe this aspect of body sway in this study.

Table 5.2.1.7: Correlation matrix: X-axis body sway measures from one factor for the rifle-shooting group (N=6, bold indicates significant at p<0.05)

	FxRange	FxSD	COPx Length	COPAbs Length	COPx VelSD	COPAbs SpeedAve
FxSD	**1.00**					
COPxLength	**0.98**	**0.98**				
COPAbsLength	0.64	0.62	0.75			
COPxVelSD	**0.98**	**0.98**	**1.00**	0.76		
COPAbsSpeedAve	0.64	0.62	0.75	**1.00**	0.76	
COPAbsSpeedSD	0.57	0.55	0.70	**0.99**	0.70	**0.99**

Absolute measures all returned high r values in correlations with X-axis measures presented in table 5.2.1.7. While none of these were significant at $p<0.05$, all absolute measures correlated significantly with Y-axis measures (table 5.2.1.8). This indicates that COPAbsLength and speed parameters were influenced more by the Y-axis. Regardless, a high degree of relatedness was evident with at least one component axis and offered no more information than that provided by the component axes.

Table 5.2.1.8: Correlation matrix: Y-axis body sway measures for the rifle-shooting group (N=6, bold indicates significant at p<0.05)

	Fy Range	Fy SD	COPy Length	COPy Range	COPy SD	COP Abs Length	COP Abs Range	COPy VelSD	COPAbs Speed Ave

FySD	**0.99**								
COPyLength	**0.86**	**0.88**							
COPyRange	**0.89**	**0.95**	**0.90**						
COPySD	**0.86**	**0.93**	**0.87**	**1.00**					
COPAbsLength	**0.98**	**0.95**	**0.88**	**0.84**	**0.80**				
COPAbsRange	**0.90**	**0.89**	0.72	**0.82**	**0.80**	**0.92**			
COPyVelSD	**0.86**	**0.88**	**1.00**	**0.90**	**0.87**	**0.88**	0.72		
COPAbsSpeedAve	**0.98**	**0.95**	**0.88**	**0.84**	**0.80**	**1.00**	**0.92**	**0.88**	
COPAbsSpeedSD	**0.96**	**0.94**	**0.90**	**0.84**	**0.81**	**0.99**	**0.90**	**0.90**	**0.99**

All Y-axis measures showed a high degree of relatedness, with only two correlations not significant at $p<0.05$ (table 5.2.1.8). On a group basis, then, this indicates all of the COPy parameters are very similar and provide the same information on body sway. This being the case, any one will adequately describe body sway in the Y-axis in this study. This finding supports the two and three factor PCA results reported previously, which found only one factor in the Y-axis measures used in this study.

However, there existed one case where PCA found a different factor existing in body sway measures used. In this case, Y-axis measures formed part of 2 separate factors. As shown in Table 5.2.1.9, Factor 2 showed high loadings with COPyLength, FyRange, FySD and COPyVelSD, while Factor 3 comprised COPyRange and COPySD, with a reasonable loading also with FyRange. This analysis indicated that two mechanisms existed within the Y-axis for this shooter. Rate of movement seems to underlie factor 2, with speed and length measures loaded highly for this factor. Amplitude of movement would seem to underlie factor 3, with a very high loading for COPyRange. For this shooter, then, two measures in the Y-axis would be required to describe body sway fully.

Table 5.2.1.9: PCA factor loading matrix with Y-axis measures split between 2 factors produced by R5 in the 5s period

(N=20 shots, loadings greater than r=0.56, p<0.01, in bold type)

	Factor 1	Factor 2	Factor 3
FxRange	**0.93**	0.13	0.07
FxSD	**0.88**	0.08	0.16
FyRange	0.00	**0.72**	0.56
FySD	0.24	**0.84**	0.38
COPxLength	**0.97**	0.14	0.05
COPxRange	**0.93**	0.06	0.18
COPxSD	**0.90**	-0.03	0.16
COPyLength	0.12	**0.96**	0.15
COPyRange	0.14	0.19	**0.94**
COPySD	0.46	0.36	**0.69**
COPAbsLength	**0.86**	0.48	0.05
COPAbsRange	**0.92**	0.06	0.21
COPxVelSD	**0.98**	0.10	0.03
COPyVelSD	0.06	**0.96**	0.21
COPAbsSpeedAve	**0.86**	0.48	0.05
COPAbsSpeedSD	**0.86**	0.10	0.14

5.2.1.3.2 Summary of PCA and cross correlation analysis

On completion of the PCA and cross correlation analysis it was decided that four measures would be used for further analysis. In different analyses, rate of movement and amplitude of movement in both X and Y axes were identified as different factors existing within the parameters measured. As such, one parameter was chosen to represent each of these factors for further analysis. These parameters were COPxRange, COPxLength, COPyRange and COPyLength. While the use of four parameters will increase redundancy in measurement (no shooter returned four factors in PCA), these four are required to ensure body sway of all individual shooters is adequately assessed. Further, it was felt that it was more important to maximise the information gain from body sway parameters.

COPxLength was chosen to represent one body sway factor identified by the PCA. This parameter was chosen based on the fact that a major aim of this study was to compare body sway and aim point fluctuation. As such, COPxLength provided a direct and more logical extension to aim point lengths than did other measures in this factor. Aim point lengths were available for analysis, while aim point speeds were not. Further, recalling from chapter 5, the error and measurement step in which COP speed/velocity is measured with indicates it is not a good measure for use in scientific research, even though the standard deviation measure will be largely independent of quantisation error. The use of force measures did not hold a logical extension to aim point fluctuation and was eliminated in preference to the more logical link between COP lengths and aim point lengths.

In the second factor identified in the X-axis, COPxRange and COPxSD measures also showed a high degree of similarity. Each parameter has associated advantages and weaknesses. Range is a reasonably logical parameter to quantify. While the range can suffer from ‘outliers’ or isolated fluctuations in the measurement period, which would yield a larger value that may not represent the whole period, these fluctuations are probably important in shooting performance. Standard deviations, on the other hand, may describe the whole sample better, but can be changed by simply increasing the time. For example, a sine curve of amplitude 10mm and frequency of 1Hz will have a range of 10mm for the 1s, 3s and 5s periods. SD, on the other hand, will decrease as time increases. Further, the better description of the whole period may decrease the effects of odd fluctuations, which are potentially important to shooting performance.

As such, it was felt that range values would be the most appropriate measure of the two for further analysis, particularly given the different periods of measure.

Y-axis measures showed greater relatedness than COPx measures, with PCA indicating only one factor was identified by the body sway measures used in all except one dataset. Further, group based cross correlations between measures were all significant at $p<0.05$. The exception to this was one data set for one shooter, in which two factors were identified in the Y-axis. For this shooter, one parameter chosen from COPyLength, COPyVelSD and Fx measures and one parameter chosen from COPyRange, COPySD and COPAbsRange was required. Based on this analysis it was decided to use both COPyRange and COPyLength to quantify body sway in the Y-axis. While one measure was indicated as being appropriate for most data sets, important data from one shooter would have been lost had only one variable been used. Further, this aligned the measurement in COPy with the measures decided upon for COPx, making for a more logical analysis overall.

The other advantage in maintaining these particular two measures for each axis as the combination of range and length/speed measures will describe the COP trace more thoroughly and provide a better representation of body sway. Range alone indicates amplitude of sway, but with no information on the speed or frequency of the trace, which may be quite different for the same range values. Length/speed values indicate the rate of movement of the COP but not amplitude or frequency, which, once again, may be quite different for the same length value. A combination of the two will report amplitude, speed and give an indication of the mean frequency of the trace.

It is appropriate here to mention a limitation of the short measurement period in shooting on the quantification of body sway parameters, particularly range and standard deviation measures. In the shorter periods, only a part of an oscillation may be captured. Values can vary depending on where this oscillation starts and finishes relative to the point of shot (the event that synchronises data capture). For example, an oscillation of 2N in 2s can be measured anywhere between 1N and 2N, depending on where the point of shot is on the curve. Figure 5.2.1.12 shows an example of this effect. The curve range between 0s and 1s, or 1s and 2s is 1N, while between 0.5s and 1.5s it is 2N. This measurement problem is a limitation of small measurement times combined with low frequency movements, but due to the important periods in shooting lying close to the point of shot and the fact that aim times lie between 4s and 12s, cannot be avoided. The length measure will be largely unaffected by this partial oscillation unless it is accompanied by a large speed fluctuation at different points in the oscillation.

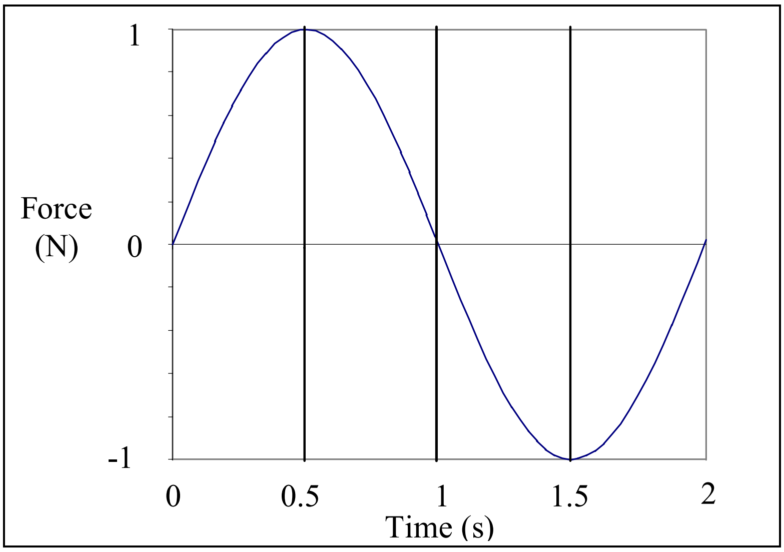


Figure 5.2.1.12: Sine curve of frequency 0.5Hz showing the measurement difficulties of short measurement periods and low movement frequencies.

It should be stressed that, with the exception of Tz, the reduction of variables was not due to their lack of importance to body sway measurement. The very low amplitudes and speeds of sway exhibited by shooters, as well as the short measurement period, resulted in minimal differences between some variables. The similarity between variables made it appropriate to reduce the number used for this study. For example, the selection of length over speed measures was due to the fact that both contained the same information, indicating each was as good an indicator of body sway as the other, but length measures were more directly linked to aim point parameters available.

5.2.2.2 Rifle: Individual Analysis

R2, who achieved the highest Result, was chosen for detailed individual analysis. All body sway, aim point and performance data for other shooters is presented in Appendix C, while results of statistical analyses are presented in Appendix F. These results have been briefly discussed in the analysis of R2 for comparison purposes and to further explore the relationship between body sway, aim point and performance on an individual basis. Statistical analyses have been presented in 5s, 3s and 1s periods separately.

To examine the collective effects of all body sway parameters on performance, multiple regression analysis was performed on body sway and performance parameters. For this analysis, one aim point parameter was eliminated to bring the ratio of independent to dependent (performance) variables to 1:5, the minimum ratio recommended by numerous researchers (eg. Tabachnick and Fidell, 1989; Thomas and Nelson, 1996). It was decided that Length would be eliminated. As LengthX and LengthY are the two components of Length, it was felt that, of the aim point variables measured, a minimal loss of data would result from elimination of this variable. Length was also eliminated for multiple regression analysis with body sway parameters. All four body sway variables were included. This bare minimum ratio of independent to dependent variables made it appropriate to discuss p values outside $p<0.05$ as potentially important.

The use of correlations followed by regression analysis is not the preferred nor ideal order of analysis. Due to the low number of shots relative to the number of parameters quantified, it was initially hoped that correlation analysis would provide enough information to explore these relationships. However, due to the range of degrees of association between different parameters for different shooters, it was felt that multiple regression analysis was appropriate, examining body sway and aim point parameters collectively, even with the limitations of sample size.

5.2.2.2.1 Shooting performance for R2

Shooting performance for R2 is displayed in table 5.2.2.2.1 (N=20 shots).

Table 5.2.2.2.1: Shooting performance for R2 (N=20 shots)

		Mean	*SD*
Result	score (max 10.9)	**10.43**	***0.32***
PosX	horizontal distance to centre of target (mm)	**1.0**	***0.7***
PosY	vertical distance to centre of target (mm)	**0.7**	***0.7***

Result for R2 of 10.43 was above the rifle shooting group average of 10.09. As mentioned above, this was the highest Result of the rifle-shooting group. Mean values for PosX of 1.0mm and PosY of 0.7mm were lower than the rifle shooting group values of 1.6mm and 1.1mm for PosX and PosY respectively. Both PosX and PosY mean values were the lowest of the group. R2 produced more error of shot on target in the X, or horizontal, axis, as indicated by the larger PosX value compared to PosY. There is no individual rifle shooting data in the literature for comparison.

5.2.2.2.2 Body sway measures and relationship with performance for R2

Table 5.2.2.2.2 shows mean values for body sway parameters for R2 (N=20 shots).

Table 5.2.2.2.2: Body sway data for 5s, 3s and 1s for R2 (N=20 shots)

		5		3		1	
		Mean	***SD***	**Mean**	***SD***	**Mean**	***SD***
COPxLength	mm	**6.79**	***0.68***	**4.01**	***0.42***	**1.22**	***0.26***
COPxRange	mm	**1.82**	***0.49***	**1.35**	***0.41***	**0.68**	***0.26***
COPyLength	mm	**6.74**	***0.89***	**3.83**	***0.68***	**1.23**	***0.34***
COPyRange	mm	**0.81**	***0.14***	**0.67**	***0.14***	**0.44**	***0.12***

As can be noted from table 5.2.2.2.2, COP lengths produced by R2 were extremely small. For example, in the 1s period, the COPxLength mean value was only 1.22mm, while COPyLength was only 1.23mm. These were smaller than the rifle group average of 1.81mm and 2.16mm for COPxLength and COPyLength respectively and were the smallest of the group. R2 differed slightly from the group, which showed a larger difference between COPyLength and COPxLength while R2 showed similar values for the two parameters for al periods. Ranges were also extremely small, with COPxRange s1 (0.68mm) and COPyRange s1 (0.44mm) below the rifle group means (1.08mm and 0.74mm for COPxRange s1 and COPyRange s1 respectively). As mentioned, no comparison data exists in the literature for standing rifle shooting.

Table 5.2.2.2.3 details the results of the correlation matrix between body sway data and shooting performance (N=20 shots).

Table 5.2.2.2.3: Correlation Matrix: Coefficients from correlations between body sway parameters in the 5s period and shot performance for R2 (N=20 shots)

	Result	PosX	PosY
COPxLength s5	**-0.35**	**0.20**	**0.32**
COPxRange s5	**-0.47***	**0.38**	**0.25**
COPyLength s5	**-0.09**	**0.01**	**0.09**
COPyRange s5	**-0.31**	**0.21**	**0.25**

(*p<0.05)

Result was correlated with COPxRange s5 (r=-0.47, p=0.04) for R2, indicating that as COPxRange decreased, Result increased (figure 5.2.2.2.1). This suggests that a decrease in body sway perpendicular to the line of shot, as measured by COPxRange, is associated with better performance in terms of score for R2. This seems a logical link, as discussed in the rifle shooing group analysis. On a general level, a lower amount of body sway might indicate greater sway control, which would be expected to be associated with better shots in terms of performance. Further, a decrease in body sway will reduce the amount of gun movement experienced (due to body sway), which may be expected to lead to reduced aim point fluctuation and better performance. However, as will be discussed later in section 5.2.2.2.4, body sway parameters were only moderately related to aim point parameters in the 5s period for R2. This, then, suggests that body sway affects performance by some other mechanism, or that it exists on a more general level, influencing other factors associated with performance as well as aim point fluctuation. This association may also be time offset, as discussed in the rifle shooting group analysis. Regardless, the mechanism in which body sway influences performance has not been identified in this study. Future work examining aim point strategies in conjunction with body sway may better define the causes of significant association between body sway in the 5s period before shot and performance for R2.

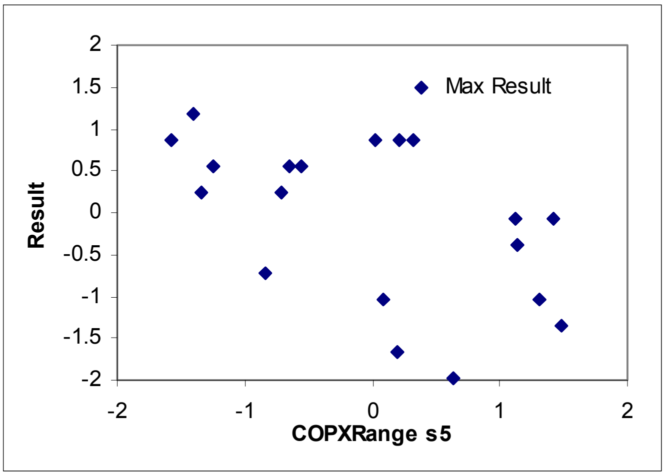


Figure 5.2.2.2.1: Scattergraph of COPxRange s5 and Result (z score) for R2.

The negative relationship between Result and COPxLength s5 ($r=-0.35$, $p=0.13$) and between Result and COPyRange s5 ($r=-0.31$, $p=0.19$) may also indicate that an increase in body sway was related to a decrease in Result for R2, although these relationships were weaker than that between COPxRange s5 and Result. In more general terms, the larger r values for correlations between COPx parameters and Result indicated that body sway perpendicular to the line of shot in the 5s period was more influential to performance than body sway parallel to the line of shot for R2. Also of interest in the data were the stronger correlations between performance, as measured by Result and PosX, and Range parameters, compared with Length parameters. Given that range indicates the amplitude of body sway by way of measuring the amplitude of COP movement, while length indicates the rate of sway movement, it may be that the amplitude of sway is more influential to performance to R2. Both range measures and length measures were represented as the more strongly associated with performance for the remaining five shooters. This issue has not been examined further in this study but may be an avenue for future research.

Two other shooters showed associations between body sway parameters in the 5s period and Result at $p<0.10$ (Appendix F). R3 returned a strong correlation between COPyLength and Result ($r=-0.57$, $p=0.01$), while R1 showed a link between COPyLength and Result ($r=0.41$, $p=0.07$). Interestingly, while an increase in body sway in the Y-axis was associated with a decrease in performance for R3 (negative correlation), the reverse was true for R1 (positive correlation), suggesting that an increase in sway was associated with an increase in performance. This is an unexpected result. It may be for R1 that an optimal level of body sway exists, and further reduction of this sway is detrimental to performance. Similar to R2, the mechanism by which body sway influences performance is unclear for R1 and R3, with both shooters showing only weak relationships between body sway (specifically

COPyLength s5) and aim point parameters. It may be that this mechanism is of a general nature, rather than specific to increased aim point fluctuation.

Also of note is body sway parallel to the line of shot was most influential on performance for R1 and R3, in contrast to the performance of R2, which was most influenced by sway perpendicular to the line of shot. The remaining three shooters showed only very weak links between body sway parameters and Result. It would seem, then, that the relationship between body sway in the 5s period and Result are related for some shooters but not for others. Further, the nature and strength of this relationship is also specific to individual shooters.

This difference between individuals highlights the group-based analysis problem. As the degree and direction of relationships were different for different shooters, it is likely that no relationship will be evident when analysed on a group basis. So while this relationship has importance for some shooters, this importance will be lost in group based analysis. This was the case in this study, with no relationship found between body sway in the 5s period and Result for the rifle-shooting group (section 5.2.2.1.2).

COPx parameters returned larger coefficients than COPy parameters in correlations between body sway and error of shot, as measured by PosX and PosY, for R2. However, these relationships were not particularly strong, with the best of these between COPxRange s5 and PosX ($r=0.38$, $p=0.10$). These positive relationships may indicate that as body sway perpendicular to the line of shot increased, the error of shot on target in the horizontal axis also increased. This is a logical result. A similar relationship was discussed in the rifle shooting group analysis between body sway and LengthX. Repeating, an increase in body sway perpendicular to the line of shot, with no accommodating movement from the upper body, will move the gun horizontally perpendicular to the line of shot, which in turn will move the aim point horizontally on the target. If this sway increases, it might be expected to generate larger errors in the horizontal, as opposed to the vertical, axis, as the aim point will be less stable in the X-axis and possibly align with rings of lower score.

Interestingly, the next strongest correlation for R2 was between COPxLength and PosY ($r=0.32$, $p=0.18$). This surprising result indicates an increase in body sway perpendicular to the line of shot may also be associated with errors in shot in the vertical axis on the target, although the correlation was not particularly strong and significant only at $p=0.18$. Numerous other shooters also showed X-Y and Y-X links between body sway and error of shot, as summarised in table 5.2.2.2.4. Logically, another factor must exist for this relationship to occur. As mentioned in the rifle shooting group analysis, body sway perpendicular to the line of shot will, with no upper body or gun movement, move the aim point horizontally on the target, while sway parallel to the line of shot will move the aim point vertically on the target. It may be that, in accommodating the sway in the X-axis by movement of the upper body and gun to reduce the aim point fluctuation in the X-axis on target, movement of the aim point in the Y-axis is also generated for these shooters. It may be that some feedback is gained from body sway in the X-axis with the aim point position in the Y-axis and between body sway in the Y-axis and aim point position in the X-axis. It may also be that these measures are performing at a general level only, and are indicating that there is a relationship between body sway and performance, rather than indicating a specific X-Y or Y-X relationship between body sway and error of shot.

Table 5.2.2.2.4: Summary of X-Y, Y-X relationships between body sway and error of shot for individual shooters (R2 excluded)

Shooter	Correlated parameters	r	p
R1	COPyRange s5 – PosX	**-0.41**	**0.07**
R3	COPyLength s5 - PosX	**0.58**	**0.01**
R4	COPyRange s5 – PosX	**-0.43**	**0.06**
R6	COPxRange s5 – PosY	**-0.48**	**0.03**

Also of interest in these results was that three of the four relationships between body sway and error of shot on target returned a negative correlation, indicating that an increase in sway was associated with a decrease in error (R1, R3, R6). This is surprising, as an increase in body sway might be expected to be associated with an increase in errors of shot on target, as discussed in the rifle shooting group section. It may be that an optimal level of body sway exists for these shooters, and further reduction of this sway is detrimental to performance, or that some feedback is gained from body sway for some individuals, in which case, an increase in body sway will increase feedback and improve performance. This will be discussed in more detail in the 1s period for R2.

As mentioned, multiple regression analysis was performed to examine the collective effects of all body sway parameters on performance. The multiple regression analysis is presented in full for the analysis of body sway in the 5s period and Result for R2, with key elements (v, R, R^2, p, Cv and the regression equation) of the remaining analyses reported. R^2, as presented in Minitab, has been reported as a percentage.

The multiple R (R) value was calculated from this data and presented in the key elements tables (although not reported in the full analysis presented). Results of these analyses for other shooters are included in Appendix F.

The best subsets output from Minitab for the analysis between body sway parameters in the 5s period and Result for R2 is presented in table 5.2.2.2.5. The number of variables (v), R^2 and Cv (total square error) are presented for each multiple regression analysis between different combinations of body sway parameters and Result. The right hand columns denote which of these variables were used in that particular analysis.

Table 5.2.2.2.5: Portion of Minitab output of best subsets regression analysis between body sway parameters in the 5s period and Result for R2

Vars (v)	R^2	Cv	COPx Length	COPx Range	COPy Length	COPy Range
1	**21.9**	**2.6**		**X**		
1	**12.4**	**4.9**	**X**			
1	**9.3**	**5.6**				**X**
1	**0.9**	**7.7**			**X**	
2	**36.1**	**1.2**		**X**		**X**
2	**25.6**	**3.8**		**X**	**X**	
2	**25**	**3.9**	**X**	**X**		
2	**19.2**	**5.3**	**X**			**X**
3	**37.1**	**3**	**X**	**X**		**X**
3	**36.6**	**3.1**		**X**	**X**	**X**
3	**29.9**	**4.7**	**X**	**X**	**X**	
3	**19.2**	**7.3**	**X**		**X**	**X**
4	**37.2**	**5**	**X**	**X**	**X**	**X**

From data in table 5.2.2.2.5, Cv was graphed against v (figure 5.2.2.2.2). The Cv = v line is also displayed. The Cv values of the best predictors cluster close to this line (Daniel and Wood, 1980). Interpretation of these graphs is somewhat ad hoc. The decision of how many variables to use was based on points close to this line. The second level of decision making involved assessing whether the increase in v improved the R^2 value appreciably at the expense of greater error. As such, regressions were specific to each analysis.

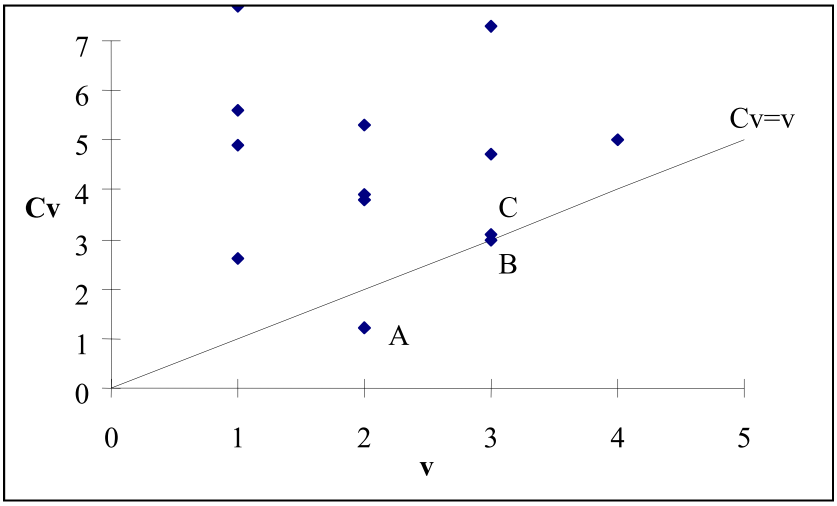


Figure 5.2.2.2.2: Cv - v graph for body sway parameters and result in the 5s period for R2 (line indicated Cv=v)

From figure 5.2.2.2.2 it can be noted that three points are close to Cv = v, one at v=2 (A) and two at v=3 (B and C). In this case, while B and C are closer to the Cv=v line, the error difference between these (Cv=3.0 and 3.1) and A (Cv=1.2) is quite large. Noting from table 5.2.2.2.5, the increase in R^2 using three as opposed to two variables is only 1%. The increase in R^2 with the addition of one variable was not considered to be adequate reason to include this variable in further analysis, given the increase in error (Cv) associated with it. As such, it was decided to proceed with two variables. This point (A) corresponded to the multiple regression that included COPxRange s5 and COPyRange s5. As such, these variables were used in the regression equation to predict Result for R2 from body sway in the 5s period. Results of this multiple regression using COPxRange s5 and COPyRange s5 as independent variables are presented in table 5.2.2.2.6, along with the selected regressions between body sway parameters and PosX and PosY.

Table 5.2.2.2.6: Best multiple regression equations for the prediction of shooting performance from body sway parameters in the 5s period for R2

	v	R	R^2	p	Cv	Regression Equation
Result	**2**	**0.60**	**36.1**	**0.02**	**1.2**	11.7 - 0.335 COPxRange s5 - 0.843 COPyRange s5
PosX	**2**	**0.46**	**21.3**	**0.13**	**1.3**	- 1.31 + 0.622 COPxRange s5 + 1.4 COPyRange s5
PosY	**2**	**0.38**	**14.6**	**0.35**	**1.6**	- 1.34 + 0.245 COPxLength s5 + 0.188

The combination of COPxRange s5 and COPyRange s5 (R=0.60, p=0.02), accounted for 36.1% of the variance in Result. While correlations between Result and COPxRange s5 returned r=-0.47 (p=0.04) and between Result and COPyRange s5 returned r=-0.31 (p=0.19), the combination of the two provided a better predictor of Result for R2. This result indicates more strongly that body sway was associated with performance in the 5s period for R2, as was discussed in the correlation analysis.

Also of interest in this analysis, range values from both the x and y axes were present in the best regression. This indicates that sway in both axes influences body sway. Also, range parameters only were evident in this regression equation, possibly supporting that sway amplitude is more influential to performance than sway rate or speed.

Two other shooters returned regressions significant at p<0.10. R3 showed a strong association between body sway and Result, as measured by COPxLength and COPyRange (R=0.61, p=0.03). Interestingly for this shooter, length in one axis and range in the other were present in the best regression equation. R1 also showed some association between body sway and Result (R=0.41, p=0.08), although only one variable, COPyLength, was included in the regression equation. As such, no more information was gained for R1 with the use of multiple regression analysis. This further supports the relationship between body sway and performance is different for different shooters at the elite level.

A combination of COPxRange and COPyRange returned R=0.46 (R^2=21.3%, p=0.13) for the regression predicting PosX for R2, an increase on the proportion of variance accounted for by the best correlation of COPxRange and PosX (r^2=14.4%). This indicates that there may be some influence of body sway on PosX for R2 although this was significant only at p=0.13 and would require more work with a larger number of shots to substantiate. Two other shooters showed relationships between body sway and PosX (R3, R= 0.61, p=0.03; R4, R=0.43, p=0.06). This indicates that, as for the relationship between body sway and Result, body sway and PosX are related for some rifle shooters, although not all.

As can be noted from table 5.2.2.2.6, body sway accounted for only 14.6% of the variance in PosY for R2 (R=0.38, p=0.35). Certainly other factors would seem to be more influential to error of shot on target in the vertical axis, as 85.4% of the variance is unexplained by the body sway parameters used. Given the very small differences between shooters in competition at the elite level, this small influence of body sway on errors of shot on target in the vertical axis may be significant to R2. However, it would seem that other skill areas hold greater potential for improvement and would be prioritised ahead of this area when attempting to improve a shooter's score. Only one shooter showed a strong relationship between body sway parameters in the 5s period and PosY (R6, R=0.48, p=0.03). This suggests that body sway and PosY are not related for most shooters in this study.

Table 5.2.2.2.7 presents coefficients from correlations between body sway parameters in the 3s period and performance for R2.

Table 5.2.2.2.7: Correlation Matrix: Coefficients from correlations between body sway parameters in the 3s period and shot performance for R2 (N=20 shots)

	Result	PosX	PosY
COPxLength s3	**-0.28**	**0.41**	**0.09**
COPxRange s3	**-0.23**	**0.37**	**-0.08**
COPyLength s3	**-0.09**	**0.00**	**0.05**
COPyRange s3	**-0.02**	**-0.07**	**-0.01**

No correlations were significant at $p<0.05$ between body sway in the 3s period and performance for R2. As was the case in the 5s period, COPx parameters returned larger coefficients than did COPy parameters (table 5.2.2.2.7), but these associations were not strong.

The correlation between COPxLength s3 and Result ($r=-0.28$, $p=0.23$) indicated that an increase in sway perpendicular to the line of shot may be associated with a decrease in Result. This is a logical result, as discussed in the 5s period analysis, although COPxLength accounted for only 8% (r^2=8%) of the variance in Result for R2 and was significant only at $p=0.23$. As discussed in the 5s period analysis, this influence still may be of interest to R2 in terms of improvement, although other factors must influence performance and improvement in these skill areas holds greater potential for improved performance.

Other shooters showed stronger links between body sway and Result in the 3s period. Correlations between body sway and Result for R3 (COPyLength s3, $r=-0.54$, $p=0.02$

and COPyRange s3, r=-0.46, p=0.05) and for R5 (COPxLength s3, r=-0.49, p=0.03) indicated, expectedly, that an increase in sway was linked to a decrease in performance for these shooters. Body sway in the X-axis was linked with performance for R5, while sway in the Y-axis was linked to performance for R3. Further, R3 showed a similar relationship in the 5s period, but R5 did not. This highlights the individuality of these results for each shooter, with degree and body swaY-axis different for different shooters, with this difference also extending to the time period before shot.

R2 showed associations between COPxLength s3 and PosX (r=0.41, p=0.07) and between COPxRange s3 and PosX (r=0.37, p=0.10), although not significant at $p<0.05$. These results indicate that an increase in COPxLength s3 and COPxRange s3 may be associated with an increase in errors of shot in the X-axis. This is a logical result, as discussed in the 5s period analysis. R5 also showed a positive relationship between COPxRange s3 and PosX (r=0.37, p=0.10). However, two shooters returned unusual results. An increase in body sway associated with a decrease in error of shot for R1 (COPyRange s3 and PosX, r=-0.42, p=0.07). Also, a Y-X relationship between body sway and error of shot was returned by R3 (COPyLength s3 and PosX, r=0.54, p=0.02; COPyRange s3 and PosX, r=0.51, p=0.02). A similar relationship was returned for R3 in the 5s period.

R2 showed no relationship between body sway and PosY (table 5.2.2.2.7). However, other shooters did show an association between body sway and PosY with R5 (PosY-COPxLength, r=0.51, p=0.02) and R6 (PosY-COPxRange, r=-0.47, p=0.04) returning correlations between these variables, significant at $p<0.05$. Once again, a ‘crossover’ of association existed (Y-X) between body sway and error of shot. Further one shooter returned a positive correlation, while the other returned a negative correlation. This further indicates individuality exists at the elite level in this relationship, with direction and degree of relationship different for different shooters, as well as 'crossover' of influence between body sway in one axis and error in the other evident in some shooters.

Table 5.2.2.2.8 presents the best multiple regression equations for the prediction of shooting performance from body sway parameters in the 3s period for R2.

Table 5.2.2.2.8: Best multiple regression equations for the prediction of shooting performance from body sway parameters in the 3s period for R2

	v	R	R^2	p	Cv	Regression Equation
Result	**1**	**0.28**	**7.8**	**0.23**	**0.2**	11.3 - 0.171 COPxLength s3
PosX	**1**	**0.41**	**16.7**	**0.07**	**0.1**	- 1.83 + 0.551 COPxLength s3
PosY	**2**	**0.16**	**2.5**	**0.81**	**1**	0.04 + 0.23 COPxLength s3 – 0.22 COPxRange s3

Multiple regression analysis did not provide any further information from the correlation analyses already performed for Result or PosX, as evident in table 5.2.2.2.8, with only one parameter present in the best regression equation. No relationship was evident between body sway parameters and PosY for R2.

Two of the remaining five shooters showed regression equations predicting Result from body sway that were significant at $p \leq 0.05$ (R3, COPxRange and COPyRange, R=0.61, p=0.03; R5, COPxRange and COPyLength, R=0.61, p=0.02). This result indicated that body sway was important to performance for some shooters in the 3s period, with the body sway parameters of importance also different for different shooters.

PosX and PosY were also found to be predicted from body sway parameters in the 3s period for other shooters, with three shooters returning regressions with PosX (R1, R3 and R5) significant at $p \leq 0.07$ and two with PosY (R5, R6) significant at $p < 0.05$. These results are similar to those found in the 5s period, with some shooters showing strong associations between body sway and performance, but not all. Further, the body sway parameters and performance indicators that were most important also differed between shooters, with body sway associated with error in both x and y axes on target.

Table 5.2.2.2.9 presents coefficients from correlations between body sway parameters in the 1s period and performance for R2.

Table 5.2.2.2.9: Correlation Matrix: Coefficients from correlations between body sway parameters in the 1s period and shot performance for R2 (N=20 shots)

	Result	PosX	PosY
COPxLength s1	**-0.19**	**0.18**	**-0.01**
COPxRange s1	**0.03**	**0.11**	**-0.20**
COPyLength s1	**0.34**	**-0.50***	**-0.08**
COPyRange s1	**0.37**	**-0.53***	**-0.08**

(*p<0.05)

Result correlated with COPyLength s1 ($r=0.34$, $p=0.15$) and COPyRange s1 ($r=0.37$, $p=0.13$), as represented in figures 5.2.2.2.3 and 5.2.2.2.4, although these relationships were significant only at $p \leq 0.15$. These relationships indicated that an increase in body sway parallel to the line of shot may be linked to an increase in shooting performance.

This is a surprising result as the opposite might be expected, as has been discussed. This relationship was also evident in one other shooter, with R1 returning correlations between Result and COPyLength s1 (r=0.41) and Result and COPyRange s1 (r=0.42), both significant at p=0.07, indicating that this was not specific to R2. As mentioned for other shooters in the 5s and 3s period analyses, there may be an optimal level of body sway for R2 and further reduction of sway beyond this level is detrimental to performance. However, as the movement produced by R2 is smaller than the minimum joint movement reported to be required to excite proprioceptors (eg. Patla, 1997) it is unlikely that any feedback would be generated from this system. It would also be unlikely that the visual and vestibular systems benefit from this movement, given its extremely small amplitude. It possibly indicates, then, a technical trait of R2 in which an optimal amount of body sway exists, after which the physical requirements of further reducing sway are counterproductive to performance, although, as R1 showed similar associations, it is not specific to R2. It could also be that sway parallel to the line of shot is linked to another factor that is influencing this result, such as movement of the upper body in response to this sway. More research with greater number of shots and measurement of other factors, such as upper body movement, is required to better define this relationship for R2.

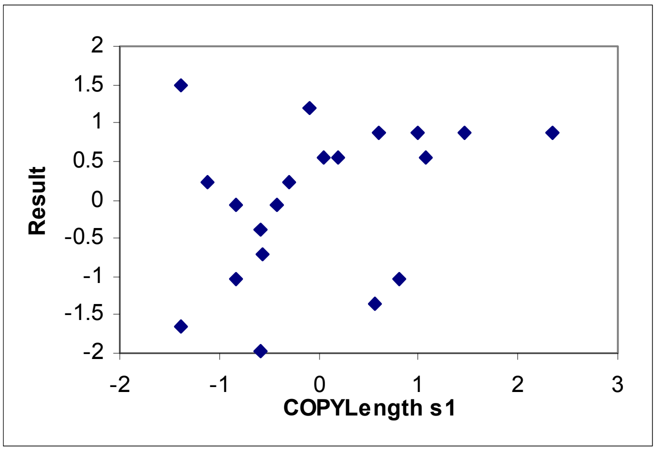


Figure 5.2.2.2.3: Scattergraph of COPyLength s1 and Result (z score) for R2.

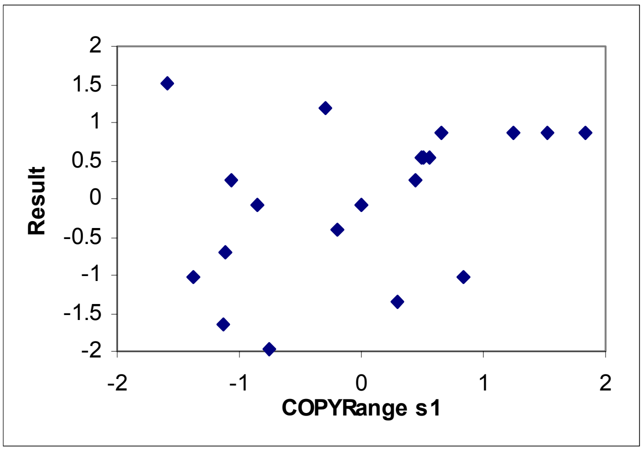


Figure 5.2.2.2.4: Scattergraph of COPyRange s1 and Result (z score) for R2.

While R2 and R1 showed a surprising relationship between body sway in the 1s period and Result, shooters showed the more logical association also, with an increase in sway associated with a decrease in performance. Results of correlations between body sway and Result returned by R3 (COPyLength s1, r=-0.40, p=0.08) and R6 (COPyRange s1, r=-0.39, p=0.09) indicated that the expected relationship existed for some shooters, although these relationships were significant only at p<0.10. A similar relationship was evident in the 5s and 3s period for R3, but not R6. This indicates that body sway is associated with Result for some shooters, with the direction of sway most influential to performance, the direction of this relationship (positive or negative), the strength of this association and the period before shot that this relationship is important varying between individuals.

PosX was significantly related to both COPyLength s1 ($r=-0.50$, $p=0.03$) and COPyRange s1 ($r=-0.53$, $p=0.02$) for R2 (figures 5.2.2.2.5 and 5.2.2.2.6). This indicated that an increase in sway parallel to the line of shot was associated with a decrease in shot errors in the horizontal axis. This is another surprising finding, with both the negative correlation and the Y-X relationship between body sway and error of shot unexpected, as discussed. No other shooter showed a Y-X association between body sway and error of shot in the 1s period, although, as reported, these relationships did exist in the longer periods. However, R5 showed a X-Y relationship between body sway and error of shot. COPxLength s1 and PosY ($r=0.48$, $p=0.03$) and COPxRange s1 and PosY ($r=0.52$, $p=0.02$) both indicated that an increase in sway perpendicular to the line of shot was associated with an increase in errors on target in the vertical axis. It is unclear what may have generated these relationships, as discussed in the 5s and 3s periods. Repeating, logically, another factor must exist for this relationship to occur. This relationship requires more research for each individual using a greater number of shots and with upper body movement monitored to better define this relationship and to identify what factor or factors may be affecting this relationship.

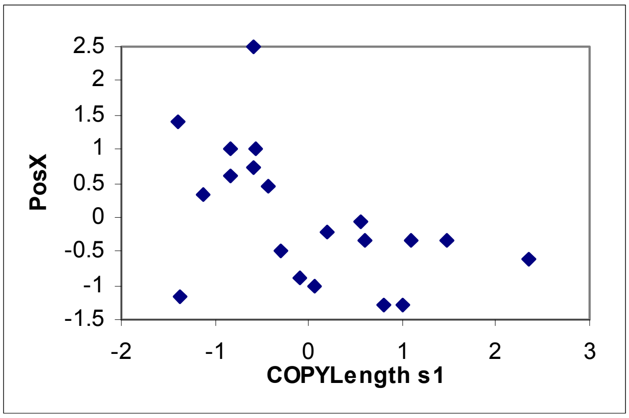


Figure 5.2.2.2.5: Scattergraph of COPyLength s1 and PosX (z score) for R2.

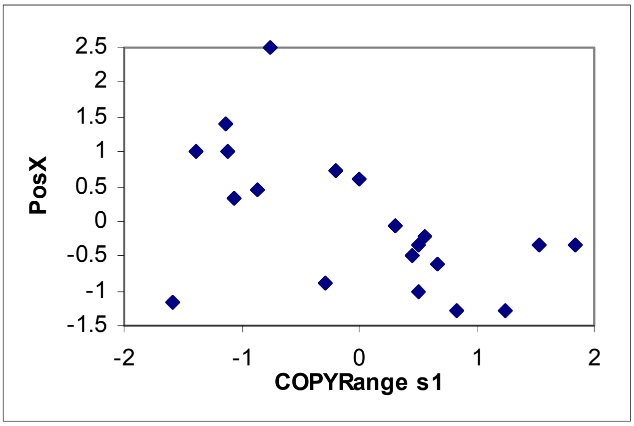


Figure 5.2.2.2.6: Scattergraph of COPyRange s1 and PosX (z score) for R2.

Table 5.2.2.2.10 presents the best multiple regression equations for the prediction of shooting performance from body sway parameters in the 1s period for R2. No more information using multiple regression was gained further to the correlation analysis already discussed, as can be noted by the single parameter equations for Result and PosX. PosY showed only a very weak relationship with body sway.

Table 5.2.2.2.10: Best multiple regression equations for the prediction of shooting performance from body sway parameters in the 1s period for R2

	v	R	R^2	p	Cv	Regression Equation
Result	**1**	**0.37**	**13.7**	**0.14**	**0.7**	10.0 + 0.316 COPyLength s1
PosX	**1**	**0.53**	**28.2**	**0.02**	**0.4**	2.39 - 3.25 COPyRange s1
PosY	**3**	**0.28**	**7.8**	**0.72**	**2.4**	0.808 + 0.579 COPxLength s1 - 0.865 COPxRange s1 - 0.212 COPyLength s1

Multiple regression analysis indicated that a relationship existed between body sway and Result, PosX and PosY for other shooters and provided more information than did the correlation analysis. R3 (including COPxLength s1, COPxRange,s1 and COPyLength s1, R=0.62, p=0.07) and R6 (including COPxLength s1, COPxRange,s1 and COPyLength s1, R=0.55, p=0.11) showed associations between body sway parameters in the 1s period and Result. R3 returned a multiple regression result for PosX of R=0.52 (p=0.10, including COPxLength s1 and COPxRange s1) while R5 showed a strong association between body sway and PosY (R=0.52, p=0.02) although only one variable, COPxRange s1, was present in the regression equation. As such, no more information was gained from the multiple regression analysis over correlation analysis for R5. This analysis provided further evidence that the relationship between body sway and performance is specific to individual shooters at the elite level, with the degree of association and parameters of influence different for different shooters.

Over all time periods, R2 showed a progressive decrease in the r-values for correlations between COPx parameters and Result from the 5s period to the 3s and 1s periods. This suggests that the influence of body sway perpendicular to the target becomes less important to performance as the point of shot approaches. It may also be that the relationship in the 5s period is related to the shots where body sway reaches a lower level earlier in the aiming process, or is held at a lower level for longer. However, no relationship was evident between Result and Aim Time (r=0.12, calculated for this comparison only). This progressive decrease in r values was not evident in other shooters (Appendix F). R2 also showed a relationship between body sway and error of shot in the 1s period but not in the 3s and 5s periods, with an increase in COPy parameters associated with an increase in PosX. As mentioned, there may be an optimal level of body sway for R2, and further reduction of this sway is detrimental to performance. This being the case, it may be that this body sway level has been reached and passed in this period. This is supported by the 1s period showing the smallest body sway ranges of any period (0.74mm). However, it remains unclear why this relationship was significant in the 1s period and not the 3s or 5s period. Other shooters also showed associations between body sway and performance in different time periods, indicating that this relationship is time dependent for different shooters.

In summary, body sway, particularly in the X-axis in the 5s period seemed to hold importance for R2. However, this importance decreased as the point of shot approached, indicating that reduction of body sway earlier in the aiming process, such that a more stable position is held for longer may be the important factor. COPy measures were linked with performance in the 1s period, but showed surprising results, with an increase in sway being associated with an increase in performance and a decrease in errors. Further, the error of shot was larger in the X-axis on target, rather than the Y-axis, as seems more logical. It is possible that a particular technical aspect of R2 causes this effect, there exists some feedback between axes or other factors are influencing this result. Body sway did not seem to influence error in the vertical axis on target for R2.

Results from other individuals indicate that body sway influences performance in elite level rifle shooting. This influence is specific to each individual, with the parameters associated, the degree and direction of this association and the important time period different for different shooters. Two of the remaining five shooters showing strong associations between body sway and Result in different time periods. Body sway was also related to PosX and PosY for different individuals in different time periods. Interestingly, all six shooters (13 correlations in total) showed X-Y and Y-X associations between body sway and errors of shot, while only R2 (1 correlation) showed an X-X or Y-Y association that was significant at $p<0.10$. It is unclear what is generating these relationships. It may be that, as mentioned for R2, some feedback is generated by body sway in one axis that assists in positioning of the aim point on the target in the other axis and which influences error in that axis. These relationships may also operate on a general level only, indicating that body sway and performance are associated. As mentioned in the rifle shooting group section (5.2.2.1), the examination of X-Y and Y-X associations between body sway and error of shot was perhaps naive and did not hold a strong theoretical basis. However, as numerous significant results have been returned, this area needs to be examined more closely, using greater numbers of shots for different individuals to define the cause of these relationships. Further, upper body and gun movement needs to be quantified.

5.2.2.2.3 Aim point measures and relationship with performance for R2

Table 5.2.2.2.11 reports mean aim point data for R2 (N=20 shots).

Table 5.2.2.2.11: Aim point data for 5s, 3s and 1s for R2 (N=20 shots)

		5s		3s		1s	
		Mean	***SD***	**Mean**	***SD***	**Mean**	***SD***
Std10.0	%time	**76.1**	***13.3***	**77.8**	***14.0***	**87.1**	***14.9***
Std10a0	%time	**85.6**	***4.9***	**89.8**	***5.7***	**98.7**	***2.0***
Length	mm	**68.6**	***4.5***	**40.3**	***2.7***	**12.6**	***1.2***
LengthX	mm	**49.7**	***4.6***	**28.8**	***2.7***	**8.5**	***1.0***
LengthY	mm	**37.3**	***2.4***	**22.3**	***1.9***	**7.4**	***1.1***

R2 was above the group average for all Std10.0 and Std10a0 measures for all periods. For example, R2 returned values of 87.1% and 98.7% for Std10.0 s1 and Std10a0 s1 respectively (table 5.2.2.2.11) which compare with the rifle group means of 72.1% and 88.4% respectively. These Std values produced by R2 were the largest in the group for all periods of measure, indicating that R2 held the most stable aim point. No data exists in the literature for comparison.

Std10.0 and Std10a0 values all increased as the measurement period decreased. This indicated that, as the point of shot approached, the aim point became both more stable and more centred on the target. The aim point remained almost entirely within the 10a0 area for the 1s period, indicating an extremely stable hold in this period. Std10a0 was larger than Std10.0 for all periods indicating that the centre of the aim point fluctuation of R2 lies on a point slightly outside the centre of the target, even in the 1s period. All individual rifle shooters produced similar results (Appendix C).

Also of note in this data is the large standard deviation in Std10.0 compared to the standard deviation in Std10a0 for all periods of measure. This suggests that, while the aim point hold, as measured by Std10a0, was reasonably consistent for all periods of measure, the accuracy of the aim point, as measured by Std10.0, was rather inconsistent. Further, it indicates that R2 does not always stabilise on the same point on the target. There was one Std10.0 s1 value of only 37.0% (shot 15 as reported in Appendix C) which influenced this standard deviation considerably. However, the standard deviation when this point was removed was ±9.9%, which is still well above the standard deviation of Std10a0 s1 of ±2.0%. A large standard deviation in Std10.0 compared to Std10a0 was evident in three of the remaining five shooters, indicating this is not specific to R2 and other shooters are also inconsistent with the centring of the aim point on target.

Aim point trace lengths were below the group average. For example, Length s1, LengthX s1 and LengthY s1 were 12.6mm, 8.5mm and 7.4mm respectively for R2 compared with 16.0mm, 11.9mm and 8.3mm respectively for the rifle shooting group. Aim point length values were the lowest aim point lengths of the group for all periods. LengthX was larger than LengthY in all periods of measure, indicating more aim point movement horizontally on the target. This is similar to the rifle shooting group characteristics (as can be noted from the group length measures mentioned in this paragraph and reported in table 5.2.2.1.4). In general terms, this may relate to the larger error in the X-axis on target, as denoted by the larger PosX value compared with PosY.

Table 5.2.2.2.12 reports coefficients from correlations between aim point data and shot performance (N=20 shots).

Table 5.2.2.2.12: Correlation Matrix: Coefficients from correlations between aim point parameters in the 5s period and shot performance for R2 (N=20 shots)

	Result	PosX	PosY
Std10.0 s5	**0.43**	**-0.33**	**-0.38**
Std10a0 s5	**-0.04**	**0.13**	**0.02**
Length s5	**0.11**	**-0.16**	**0.10**
LengthX s5	**0.01**	**-0.02**	**0.12**
LengthY s5	**0.30**	**-0.38**	**-0.06**

The correlation between Std10.0 s5 and Result returned the strongest correlation between aim point parameters in the 5s period and performance ($r=0.43$, $p=0.07$), indicating that an increase in Std10.0 was associated with an increase in Result, although not significant at $p<0.05$. This is a logical link, as discussed in the rifle shooting group section. Repeating, a greater time spent by the aim point in the 10.0 ring increases the chances of the aim point inside this ring at the point of shot and hence scoring more highly than an aim point which lies outside this area for longer periods. Figure 5.2.2.2.7 shows this relationship for R2. Noticeable from this figure is a positive relationship between the variables, although there are obvious points that are distinct from this pattern. One other shooter (R5) also returned a positive relationship, significant at $p<0.05$, between Std10.0 s5 and Result ($r=0.50$, $p=0.03$), indicating that this relationship is important for some, but not all shooters.

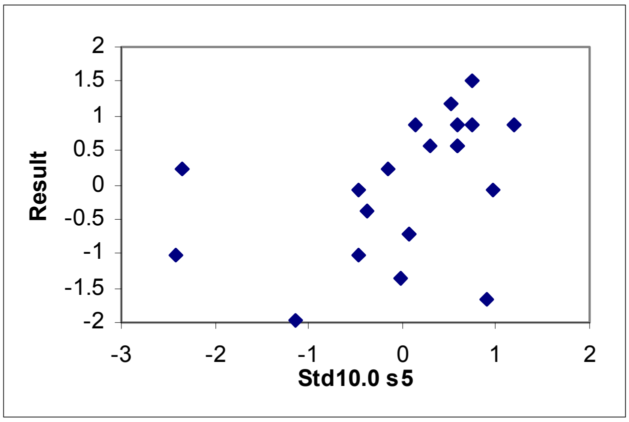


Figure 5.2.2.2.7: Scattergraph of Std10.0 s5 and Result (z score) for R2.

LengthY s5 was the only other parameter to show some association with Result ($r=0.30$, $p=0.20$) for R2, indicating an increase in LengthY s5 may be associated with an increase in Result. Although this relationship was not particularly strong and significant only at $p=0.20$, it was surprising. As discussed in the rifle shooting group analysis, an increase in aim point length might suggest less aim point control, which would be expected to be associated with poorer performance. More specifically, as there is greater aim point movement, it may be aligned with the target centre less frequently and may pass over lower score rings. However, a larger aim point length does not necessarily relate to a larger area within which the aim point is moving. The aim point can stay within a small area but fluctuate rapidly to achieve a longer trace. The fact that an increase in both LengthY s5 and Std10.0 s5 were associated with an improved performance suggests that the aim point in the Y-axis is moving only within a small area, or is mostly centred on the target centre for R2. As such, the larger LengthY value may not be related to poorer aim control for R2, or an aim point strategy may be influencing this measure, which in turn influenced this result. However, both parameters were included in the regression equation between aim point parameters and Result, indicating that there is independent contribution of these parameters and that both occur and influence performance. The association between an increase in aim point length with an increase in performance was not evident in other shooters (Appendix F) in the 5s period.

R2 showed some association between Std10.0 s5 and PosX ($r=-0.33$, $p=0.15$) and between Std10.0 s5 and PosY ($r=-0.38$, $p=0.10$) for R2. Both negative correlations indicated that an increase in aim point steadiness was associated with a decrease in error in both the horizontal and vertical axes. This result is logical, as discussed in the rifle shooting group analysis, as a larger Std10.0 score might indicate greater aim point control, which would be expected to be associated with reduced error. More specifically, less error will be produced if the aim point remains closer to the target centre for longer, as indicated by the Std10.0 measure. This relationship is not distinct to R2, with R4 also returning a negative correlation between Std10.0 s5 and PosX ($r=-0.37$, $p=0.11$) and between Std10.0 s5 and PosY ($r=-0.33$, $p=0.15$). This also indicated that an increase in aim point steadiness may be associated with a decrease in error, although with coefficients of $r<0.40$ for both R2 and R4, these relationships were not strong. This result provides another example of a relationship may be important to some but not all shooters.

LengthY s5 showed some association with PosX ($r=-0.38$, $p=0.10$) for R2. This result is unusual. An increase in LengthY suggests a reduced aim point control, which might be expected to be associated with poorer performance and an increase in error, as discussed. While one shooter returned the more expected positive relationship between aim point length and error of shot in the 5s period (R4, LengthY s5 - PosY, $r=0.47$, $p=0.04$), two shooters returned a negative correlation, similar to R2 (R1, LengthX s5 - PosX, r=-0.38, p=0.07 and LengthY s5 - PosY, r=-0.41, p=0.07; R6, LengthY s5 - PosX, r=-0.44, p=0.05). As mentioned in discussion of the relationship between LengthY s5 and Result, a larger aim point length does not necessarily relate to a larger area in which the aim point moves. As such, the trace may fluctuate rapidly, but within a small area around the centre of the target and minimising errors. However, this only explains why no relationship might exist between aim point length and error of shot, rather than why it is associated with a decrease in error. Some aim point length may be useful in terms of feedback to R2 (as well as R1 and R6) or there may exist an optimal amount of aim point fluctuation in the Y-axis, after which further reduction is detrimental to performance. Aim point strategies may also exist. The causes of this relationship remain unclear and requires further examination of the aim point better define the relationship between LengthY s5 and PosX for R2.

The other unusual aspect of this relationship is the Y-X association of aim point length in the Y-axis and error in the X-axis. Logically, Y-axis fluctuation would be expected to be associated with Y-axis errors, as found in other shooters (R1 and R4, as reported in the previous paragraph), as aim point fluctuation in the Y-axis will obviously have a direct bearing on the position of the aim point in the Y-axis at any time and particularly at the point of shot. However, R6 also returned a negative correlation between LengthY s5 and PosX (r=-0.44, p=0.05), indicating that this relationship is not peculiar to R2. It is unclear what may be generating this relationship. It may be that vertical aim point fluctuation may generate useful feedback for the position of the aim point relative to the target centre in the horizontal axis. It is also possible that an aim point strategy, as mentioned previously, is affecting these results. However, the association of LengthY and PosX remains unclear. More research with upper body and gun movement monitored as well as aim point strategies accounted for is required to form a more definitive answer for this relationship for R2.

Table 5.2.2.2.13 presents the best multiple regression equations for the prediction of shooting performance from aim point parameters in the 5s period for R2.

Table 5.2.2.2.13: Best multiple regression equations for the prediction of shooting performance from aim point parameters in the 5s period for R2

	v	R	R^2	p	Cv	Regression Equation
Result	**2**	**0.57**	**32.4**	**0.04**	**1.3**	7.62 + 0.0116 Std10.0 s5 + 0.0515 LengthY s5
PosX	**2**	**0.55**	**30.3**	**0.05**	**1.4**	7.88 – 0.0226 Std10.0 s5 - 0.14 LengthY s5
PosY	**1**	**0.38**	**14.7**	**0.10**	**-0.4**	2.09 – 0.0187 Std10.0 s5

Aim point variables (Std10.0 s5 and LengthY s5) accounted for 32.4% (R=0.57, p=0.04) of the variance in Result for R2. As mentioned, this indicates an independent contribution was made by both Std10.0 s5 and LengthY s5 to Result. R4 also returned a regression equation significant at $p<0.05$ (R=0.50, R^2=25.4. p=0.02), although only one variable (Std10.0 s5) was present in the equation. Std10.0 s5 and LengthY s5 also combined to account for 30.3% of the variance in PosX for R2 (R=0.55, p=0.05). As for Result, PosX was better predicted by a combination of these two aim point parameters for R2. This further indicated that aim point fluctuation and performance were related for R2, with Std10.0 s5 and LengthY s5 the important indicators. R6 was the only other shooter to return a regression significant at $p\leq0.05$ (R=0.44, p=0.05), although only one parameter was present in the best regression equation (LengthY s5).

Multiple regression did not provide any more information from correlation analysis between aim point parameters and PosY for R2, with only one variable included in the best regression equation. This was also the case for the two other shooters who showed associations between aim point parameters and PosY (R1, R4, Appendix F) significant at $p<0.10$. These relationships have been discussed in association with the correlation analysis in this period.

Table 5.2.2.2.14 reports coefficients from correlations between aim point parameters in the 3s period and shot performance (N=20 shots).

Table 5.2.2.2.14: Correlation Matrix: Coefficients from correlations between aim point parameters in the 3s period and shot performance for R2 (N=20 shots)

	Result	PosX	PosY
Std10.0 s3	**0.18**	**-0.04**	**-0.40**
Std10a0 s3	**-0.12**	**0.16**	**0.05**
Length s3	**0.31**	**-0.30**	**-0.05**
LengthX s3	**0.17**	**-0.15**	**0.03**
LengthY s3	**0.32**	**-0.30**	**-0.17**

(*p<0.05)

Aim point parameters in the 3s period and Result were not related at $p<0.05$ for R2. Length s3 ($r=0.31, p=0.18$) and LengthY s3 ($r=0.32$, $p=0.17$) were the strongest of these relationships, but were significant only at $p<0.20$. Both indicated that as aim point length increased, Result increased. This unexpected result also occurred in the 5s period for R2 and was discussed in that section (5.2.2.2.2). However, the correlation coefficient for this relationship suggests that aim point fluctuation does not influence Result strongly in the 3s before shot for R2. Similarly, other shooters showed only weak relationships between aim point lengths and Result, with the strongest of these returned by R1 (r=-0.22, p=0.35), which might indicate that aim point lengths in the 3s period before shot do not influence result for most elite rifle shooters. In fact, for all correlations between aim point parameters in the 3s period and Result, only one shooter returned a correlation significant at p<0.20 (R3, Std10a0 s3, r=0.40, p=0.08). This suggested that aim point fluctuation in the 3s period was not of particular importance to most shooters in this study.

Aim point parameters in the 3s period showed moderate associations with PosX and PosY for R2. Std10.0 s3 and PosY (r=-0.40, p=0.08) indicated that an increase in aim point steadiness may be associated with a decrease in error in the vertical axis. This result is expected, as discussed in the analysis of aim point parameters in the 5s period. Also showing some association, although not strong, Length s3 and PosX (r=-0.30, p=0.20) and LengthY s3 and PosX (r=-0.30, p=0.20) indicated that an increase in aim point length may be linked with a decrease in errors. Both the negative relationship and Y-X association were unexpected. LengthYs5 and PosX were also related in the 5s period for R2 (r=-0.38, p=0.10). No other shooter showed a relationship between LengthY s3 and PosX nor between LengthX s3 and PosY significant at p<0.30, indicating that this unusual result is distinct to R2 for this group, although in both 5s and 3s periods, this relationship was not strong. It is unclear what may be generating these relationships for R2.

Table 5.2.2.2.15 presents the best multiple regression equations for the prediction of shooting performance from aim point parameters in the 3s period for R2.

Table 5.2.2.2.15: Best multiple regression equations for the prediction of shooting performance from aim point parameters in the 3s period for R2

	v	R	R^2	p	Cv	Regression Equation
Result	**3**	**0.48**	**23**	**0.23**	**3.3**	7.48 + 0.00788 Std10.0 s3 + 0.0318 LengthX s3 + 0.0636 LengthY s3
PosX	**1**	**0.30**	**9**	**0.21**	**-0.1**	4.64 - 0.115 LengthY s3
PosY	**2**	**0.48**	**22.8**	**0.11**	**1.5**	4.31 - 0.0211 Std10.0 s3 - 0.0898 LengthY s3

Aim point parameters accounted for 23.0% (R=0.48) of the variance in Result, although this was significant only at p=0.23. This suggests there may be some influence of aim point fluctuation in the 3s period on performance for R2. However, with the fairly poor p value returned, more research with a greater number of shots would be required to substantiate this relationship for R2. Only one shooter returned a regression between aim point fluctuation in the 3s period and Result significant at p<0.20 (R3, Std10.0 and Std10a0, R=0.49, R^2=23.8, p=0.13). This suggests that aim point fluctuation in the 3s period did not strongly influence Result for rifle shooters in this study.

No more information was gained from multiple regression analysis for PosX, with LengthY s3 the only parameter included in the best regression equation for R2. This relationship was discussed in the correlation analysis. The multiple regression result suggests that aim point parameters had only a small influence on errors of shot in the X-axis for R2. This was the case for most other shooters also, with only R3 showing a relationship between aim point parameters in the 3s period and PosX (R=0.49, R^2=24.1, p=0.13) significant at p<0.20. As mentioned with respect to body sway, aim point fluctuation may still be of importance to these rifle shooters, but there must be other factors that are influencing performance.

Std10.0 s3 and LengthY s3 were included in the best regression predicting PosY ($R=0.48$, $R^2=22.8$, $p=0.11$) for R2. This indicates that aim point parameters in the 3s period have some influence on PosY, although with only 22.8% of the variance in PosY accounted for by aim point parameters, there are obviously other factors influencing PosY. Std10.0 and LengthY seem to be important parameters for R2, with these the only aim point parameters to feature in regressions in the 5s and 3s period. LengthY also featured in regressions returned by R1 (LengthY s3, $R=0.39$, $R^2=15.4$, $p=0.09$) and R4 (LengthY s3, $R=0.46$, $R^2=21.2$, $p=0.05$).

Overall, then, it would seem that the 3s period holds some interest for R2, although, based on the stronger correlation coefficients and multiple R values between aim point and performance parameters, the 5s period (as discussed) and 1s period (discussed later) seem to be more important.

As noted in the rifle group section (5.2.2.1), Std10a0 began to 'top out' or clip (score 100%) in the 3s period. R2 returned two 100% scores in the 3s period and 13 scores of 100% in the 1s period for the 20 shots (Appendix C). This reduced the effectiveness of this measure as discerning between shots as well as adversely affecting the statistical analysis. Other shooters returned only three 100% scores in the 1s period and none in the 3s period, indicating that for this analysis overall, this clipping would not have influenced results greatly, with the possible exception of R2. The use of an area defined by the 10.5 ring would be more suitable for individual analysis of rifle shooting, effectively increasing the measurement precision and the range of measures used, as well as reducing the number of 100% scores in the 3s and 1s period.

Table 5.2.2.2.16 reports coefficients from correlations between aim point parameters in the 1s period and shot performance (N=20 shots).

Table 5.2.2.2.16: Correlation Matrix: Coefficients from correlations between aim point parameters in the 1s period and shot performance for R2 (N=20 shots)

	Result	PosX	PosY
Std10.0 s1	**0.18**	**0.08**	**-0.46***
Std10a0 s1	**0.16**	**-0.09**	**-0.26**
Length s1	**-0.05**	**-0.18**	**0.33**
LengthX s1	**0.14**	**-0.29**	**0.14**
LengthY s1	**-0.20**	**0.05**	**0.32**

(*p<0.05)

Interestingly, aim point parameters were not strongly associated with Result in the 1s period for R2. This lack of association is perhaps unusual. The aim point itself is directly related to performance, as the location of the aim point at the point of shot is the measure of performance. Further, this relationship might be expected to be most important in the 1s period before shot, as opposed to the longer periods as the closer to shot, the more important the location of the aim point becomes. As mentioned, it is possible that the aim point parameters used did not adequately describe aim point fluctuation for R2. This would particularly be the case if the aim point strategy of R2 was to time the point of shot such that it coincides with the aim point passing across the target centre (a 'reaction' shooter as described by Zatsiorski and Aktov, 1990). Also, aim point parameters would have been less sensitive if R2 alternated strategies during the course of the 20 shots. This ability to alternate between aim point strategies was noted by Heinula (1996) in elite level shooters. However, without the raw aim point co-ordinates, more thorough analysis of aim point fluctuation was not possible. Further, Heinula presented a regression equation in which triggering, not measured in this study, was included as a variable which influenced performance. It could also be that it is necessary to examine this relationship on a shot to shot basis, as the importance of aim point fluctuation may not be consistent across a number of shots, such as the 20 used in this study. These factors remain as limitations of this study and may have influenced the finding that aim point parameters in the last second before shot and Result were largely unrelated for R2.

However, in contrast to the results of R2, all other shooters showed relationships between aim point parameters and Result significant at $p<0.18$, as summarised in table 5.2.2.2.17. This suggests that this result was specific to R2, and the possible limitations of measurement did not seem to influence other shooters.

Table 5.2.2.2.17: Summary strongest correlations between aim pint parameters and Result for rifle shooters (R2 excluded)

Shooter	Aim point parameter	r	p
R1	LengthY s1	**-0.55**	**0.01**
R3	Std10.0 s1	**0.33**	**0.17**
R4	Std10.0 s1	**0.46**	**0.05**
R5	Std10a0 s1	**0.31**	**0.18**
R6	Std10.0 s1	**0.32**	**0.17**

R2 did show an association between aim point fluctuation and error of shot on target. PosY was significantly correlated with Std10.0 s1 ($r=-0.46$, $p=0.05$). This indicated that a decrease in aim point steadiness, as measured by Std10.0 s1, was associated with an increase in the vertical error of shot on target. As discussed in the 5s period analysis, this is a logical result. The scattergraph of this relationship, displayed in figure 5.2.2.2.8, shows that a large and a small group seem to exist in the data. This may be due to another factor that is influencing this relationship, or a different aim point strategy being employed by R2 for different shots. It may also be simply five poor shots, as they represent the largest PosY scores and make up the majority of the low Std10.0 scores. Regardless, this distribution of data points obviously would have influenced statistical analysis. If two groups do, in fact, exist, then the correlation has been exaggerated. It may also accurately represent the relationship between Std10.0 s1 and PosY. This cannot be concluded without more research with a larger number of shots and with analysis of aim point strategies for R2.

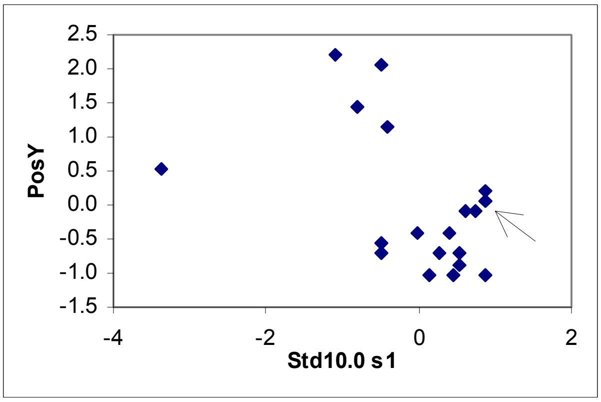


Figure 5.2.2.2.8: Scattergraph of Std10.0 s1 and PosY (z score) for R2 (note: two points, denoted by arrow, are located on the same co-ordinates).

Three other shooters also showed relationships between Std10.0 s1 and PosY significant at $p \leq 0.20$ (R1, r=-0.30, p=0.20; R4, r=-0.30, p=0.20; R5, r=-0.32, p=0.17). All indicated that an increase in Std10.0 s1 was associated with a decrease in PosY, although these were not as strong as the relationship for R2.

Correlations between PosY and Length s1 (r=0.33, p=0.15) and PosY and LengthY s1 (r=0.32, p=0.16) indicated that an increase in aim point length in the Y-axis and overall may be associated with an increase in error in the Y-axis on target for R2. R1 showed a similar link between LengthY s1 and PosY ($r=0.53$, $p=0.02$). These relationships are logical, as discussed in the 5s period.

Interestingly for R2, LengthY in the 3s period ($r=-0.32$, $p=0.17$) and 5s period ($r=-0.38$, $p=0.10$) was associated more closely with PosX, while in the 1s period, these parameters were unrelated ($r=0.05$). This suggests that the association between LengthY and PosX was generated in the periods between 1s and 5s before shot. Further, this relationship is unimportant in the 1s period. As discussed in the analysis of the 5s and 3s periods, there may be some useful feedback for the horizontal position of the aim point on the target that is gained from vertical aim point movement. However, this feedback may only assist in locating the aim point close to the centre in the early stages of aiming (5s-1s before shot), after which other factors become more influential. It may also be that the fluctuation in the 1s period is too small to provide feedback for positioning the aim point horizontally on target.

PosX generally showed only weak associations with aim point parameters in the 1s period for R2, with the strongest of these between PosX and LengthX s1 ($r=0.29$, $p=0.21$). This relationship indicated an increase in aim point length in the horizontal axis may be associated with an increase in error in the horizontal axis on target, as might be expected. All other shooters showed one correlation between PosX and aim point parameters significant at $p<0.20$ ($r>0.30$), although the best of these (R6, LengthY s1, $r=-0.39$) was significant only at $p=0.09$. This indicates that aim point fluctuation in the last second before shot may have some association with error of shot in the horizontal axis for rifle shooters, although this influence is not particularly strong.

Table 5.2.2.2.18 presents the best multiple regression equations for the prediction of shooting performance from aim point parameters in the 1s period for R2.

Table 5.2.2.2.18: Best multiple regression equations for the prediction of shooting performance from aim point parameters in the 1s period for R2

	v	R	R^2	p	Cv	Regression Equation
Result	**3**	**0.48**	**22.6**	**0.24**	**3.6**	1.8 + 0.0093 Std10.0 s1 + 0.0632 Std10a0 s1 + 0.184 LengthX s1
PosX	**2**	**0.41**	**16.7**	**0.21**	**1.5**	16.4 - 0.127 Std10a0 s1 - 0.341 LengthX s1
PosY	**4**	**0.62**	**38.5**	**0.10**	**5**	16.4 - 0.0228 Std10.0 s1 - 0.132 Std10a0 s1 - 0.227 LengthX s1 + 0.161 LengthY s1

Multiple regression analysis provided stronger support than correlation analysis that aim point fluctuation and Result were associated for R2. Aim point parameters accounted for 22.6% of the variance in Result, with three variables contributing to this value (table 5.2.2.2.18). However, this relationship was significant only at p=0.24. More research with a larger number of shots is required to substantiate the relationship for R2. Further, other factors are influencing this result with 77.4% of the variance was not accounted for by aim point parameters for R2.

Three of the other five shooters tested returned regressions between aim point parameters and Result that were significant at $p \leq 0.10$, as summarised in table 5.2.2.2.19. As can be noted from this table, all shooters showed different degrees of association, as evident by R and R^2 values, between aim point parameters and Result. Further, different parameters made up the best regression equations for different individuals. These results indicate that aim point fluctuation is important to some shooters in the 1s period before shot, but not others, with this relationship specific to the individual shooter. The inclusion of all aim point parameters in table 5.2.2.2.19

may have implications for shooters in terms of biofeedback applications. With different aim point parameters important for different shooters, in terms of feedback, a larger number of parameters would seem to be recommended in the first stages of analysis to identify which are important for that particular shooter.

Table 5.2.2.2.19: Regressions between aim point fluctuation in the 1s period and Result for individual shooters significant at p<0.05

Shooter	Aim point parameters included in best regression	R	R^2	p
R1	LengthX s1 and LengthY s1	**0.64**	**41.3**	**0.01**
R4	Std10.0 s1, Std10a0 s1 and LengthY s1	**0.59**	**35.1**	**0.07**
R5	Std10a0 s1, LengthX s1 and LengthY s1	**0.55**	**30.8**	**0.10**

The regression for R2 between PosY and aim point parameters (R=0.62, R^2=38.5, p=0.10) indicated that aim point fluctuation contributed to errors of shot in the vertical axis on target. All four parameters were present in the best regression equation (table 5.2.2.2.18). Interestingly, only Std10.0 and LengthY featured in regressions in the 5s and 3s periods. It may be that PosY becomes more sensitive to aim point fluctuation generally in this last second before shot. Other shooters also showed associations between aim point parameters and PosX and PosY at p≤0.11 as summarised in table 5.2.2.2.20. These results indicated, as found in correlation analysis, that aim point fluctuation is associated with error of shot on target, but this association is very specific to different shooters, with the degree of association and the aim point parameters most influential to performance different for different individuals.

Table 5.2.2.2.20: Summary of regressions significant at p≤0.11 between aim point parameters in the 1s period and error of shot for individual shooters (R2 excluded)

	Shooter	Parameters	R	R^2	p

PosX	R4	LengthY s1	**0.37**	**13.7**	**0.11**
	R5	Std10a0 s1, LengthX s1, LengthY s1	**0.55**	**30.6**	**0.11**
	R6	LengthY s1	**0.39**	**15.5**	**0.09**
PosY	R4	LengthY s1	**0.53**	**28.5**	**0.04**
	R5	Std10a0 s1, LengthX s1	**0.49**	**24.0**	**0.10**
	R6	Std10a0 s1, LengthX s1	**0.67**	**45.4**	**<0.01**

In summary, R2 exhibited a very stable aim point, as evident by the high values returned in Std measures and small aim point lengths, which were the best in the group in all periods. However, the accuracy of aim of R2 was inconsistent, as indicated by a large standard deviation of Std10.0. In general terms, a link between aim point fluctuation and performance might be indicated by R2 achieving the best scores of the group for both Std and aim point length measures. This was the case in the 5s period, with an increase in aim point steadiness being associated with an increase in performance, although only weak to moderate relationships were evident in the 3s and 1s periods. This was not distinctive of R2, as two other shooters also showed associations in the 5s period, but not in the 3s and 1s periods between Std measures and performance. However, the remaining three shooters in the group did show strong associations in the 1s period, indicating that an increased aim point steadiness and reduced aim point lengths were associated with an increase in the shot score and a reduction in errors of shot. Generally, then, it seemed that aim point fluctuation was associated with performance for the shooters tested, with different combinations of variables present in the best prediction equations in multiple regression analysis, the period most important and the performance variables most affected being specific to each shooter.

5.2.2.2.4 Relationship between body sway and aim point parameters for R2

Table 5.2.2.2.21 reports coefficients from correlations between body sway and aim point parameters in the 5s period (N=20 shots).

Table 5.2.2.2.21: Correlation Matrix: Coefficients from correlations between body sway and aim point parameters in the 5s period for R2 (N=20 shots)

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s5	**-0.06**	**-0.15**	**0.02**	**-0.14**
Std10a0 s5	**-0.12**	**-0.35**	**-0.04**	**-0.04**
Length s5	**0.28**	**-0.13**	**-0.25**	**0.09**
LengthX s5	**0.34**	**-0.06**	**-0.26**	**0.07**
LengthY s5	**-0.07**	**-0.24**	**-0.07**	**0.03**

No relationships between body sway and aim point were significant at $p<0.10$ for R2. COPxRange s5 correlated with Std10a0 s5 ($r=-0.35$), indicating an increase in sway perpendicular to the line of shot may be associated with a decrease in aim point steadiness, although this relationship was significant only at $p=0.13$. This result is logical, as discussed in the rifle shooting group analysis. Repeating, an increase in body sway will increase gun movement, which will in turn increase the area over which the aim point moves on the target. The only other correlation that was significant at $p<0.20$ was between COPxLength s5 and LengthX s5 ($r=0.34$, $p=0.14$). This result is also a logical and expected one, for the same reasons. Also, sway perpendicular to the line of shot might be expected to move the aim point horizontally (X-axis) on the target. However, the correlation coefficients in table 5.2.2.2.21 indicate only a weak to moderate relationship exists between body sway and aim point fluctuation for R2.

While correlations between body sway and aim point parameters were not strong in the 5s period for R2, this was not the case for other shooters. Four shooters returned at least one correlation that was significant at $p<0.05$, with the remaining shooter (R3) returning one correlation that was significant at $p=0.08$. Table 5.2.2.2.22 reports the strongest correlation for each shooter. All correlations for these shooters significant at $p<0.05$ (eighteen in all, Appendix F) indicated that an increase in body sway was associated with an increase in aim point length and a decrease in aim point steadiness, as expected. This suggests that aim point fluctuation and body sway in the 5s period are related for most shooters, with a more stable stance being associated with a more controlled and steady aim point.

Table 5.2.2.2.22: Strongest correlations for individual shooters between body sway and aim point parameters in the 5s period (R2 excluded)

	Parameters	r	p
R1	COPxLength s5 - LengthX s5	**0.73**	**<0.01**
R3	COPyRange s5 - LengthY s5	**-0.42**	**0.08**
R4	COPyLength s5 - Length s5	**0.52**	**0.02**
R5	COPyLength s5 - LengthY s5	**0.56**	**0.01**
R6	COPyLength s5 - Length s5	**0.63**	**<0.01**

Table 5.2.2.2.23 presents the best multiple regression equations for the prediction of aim point parameters from body sway parameters in the 5s period for R2.

Table 5.2.2.2.23: Best multiple regression equations for the prediction of aim point parameters from body sway parameters in the 5s period for R2

	v	R	R^2	p	Cv	Regression Equation
Std10.0 s5	**2**	**0.22**	**5**	**0.65**	**1.4**	97.1 -4.76 COPxRange s5 - 15.3 COPyRange s5
Std10a0 s5	**2**	**0.45**	**20.1**	**0.15**	**1.3**	92.3 + 4.69 COPxRange s5 - 2.25 COPxLength s5
LengthX s5	**2**	**0.42**	**17.7**	**0.19**	**2.4**	57.5 - 2.83 COPxLength s5 + 13.9 COPxRange s5
LengthY s5	**1**	**0.24**	**5.9**	**0.30**	**-0.6**	39.4 - 1.16 COPxRange s5

Body sway did not seem to influence aim point fluctuation strongly in the 5s period, with no relationship significant at $p<0.15$. Std10.0 s5 was not associated with body sway parameters for R2. The best regression obtained from body sway parameters accounted for only 5% of the variance in Std10.0 s5 (R=0.22, p=0.65). This suggests that factors other than body sway influence the accuracy of the aim point, as measured by Std10.0, in the 5s period before shot. Similarly, four of the remaining five shooters showed no association between body sway parameters and Std10.0 s5. This might indicate that these factors are not related for most shooters. However, body sway parameters accounted for 50.2% of the variance in Std10.0 s5 for R1 (R=0.71,

R^2=50.2, p=0.01), indicating a strong relationship existed between these variables for this shooter. Once again, this result highlights the individuality of results between these variables for elite rifle shooters.

Std10a0 s5 was predicted by two body sway parameters, COPxRange s5 and COPxLength s5 (R=0.45, R^2=20.1) for R2, significant at p=0.15. This indicated as discussed in the correlation analysis for R2, that body sway had some influence on Std10a0 s5, although this influence is not particularly strong. Body sway perpendicular to the line of shot seemed to be the most influential axis of the sway axes on Std10a0, with both COPxRange and COPxLength present in the equation. Two other shooters showed strong associations between body sway parameters and Std10a0 s5 (R1, R=0.68, R^2=45.7, p=0.02: R6, R=0.59, R^2=34.5, p=0.03) significant at $p<0.05$. This indicated that body sway influences aim point steadiness, as measured by Std10a0, for some, but not all shooters.

The same parameters also best predicted LengthX s5 (R=0.42, R^2=17.7) at p=0.19 for R2. This indicated that body sway influenced aim point fluctuation in the horizontal axis on target, although not strongly. Further, with p=0.19, more work with a larger N would be required to substantiate this relationship. Strong regressions were returned by two shooters predicting LengthX s5 from body sway parameters (R1, R=0.86, R^2=74.3, $p<0.01$; R6, R=0.54, R^2=28.9, p=0.01). This indicated that body sway influenced aim point fluctuation in the horizontal axis on target for most shooters, with this influence varying in degree for different shooters.

LengthY s5 did not seem to be related to body sway parameters for R2. However, the five remaining shooters returned regressions between body sway parameters and LengthY s5 that were significant at $p<0.10$, as summarised in table 5.2.2.2.24. This suggested body sway and LengthY s5 were related strongly for most shooters, with R2 the exception in this group. It may be that R2 is more skilled at accommodating body sway with upper body and gun movements compared to the rest of the group. Given that R2 achieved the best performance, the lowest body sway scores and the smallest LengthY s5 scores in the group lends support to this possibility. However, as will be discussed later, R2 did show associations between body sway and aim point parameters in the 3s period, indicating that this association may also be dependent on the time period, rather than a skill factor alone.

Table 5.2.2.2.24: Results of multiple regression analysis between body sway parameters and LengthY s5 for individual shooters (R2 excluded)

	R	R^2	p
R1	**0.57**	**33.1**	**0.01**
R3	**0.42**	**17.8**	**0.08**
R4	**0.70**	**49.0**	**0.01**
R5	**0.56**	**30.9**	**0.01**
R6	**0.67**	**44.9**	**0.02**

Table 5.2.2.2.25 reports coefficients from correlations between body sway and aim point parameters in the 3s period (N=20 shots).

Table 5.2.2.2.25: Correlation Matrix: Coefficients from correlations between body sway and aim point parameters in the 3s period for R2 (N=20 shots)

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s3	**-0.09**	**0.00**	**0.24**	**0.38**
Std10a0 s3	**-0.45***	**-0.36**	**0.31**	**0.52***
Length s3	**0.03**	**0.08**	**-0.30**	**-0.47***
LengthX s3	**-0.05**	**-0.02**	**-0.24**	**-0.30**
LengthY s3	**0.16**	**0.22**	**-0.23**	**-0.44**

(*p<0.05)

Std10a0 s3 was related to COPxLength s3 (r=-0.45, p=0.05) for R2, as represented by the scattergraph in figure 5.2.2.2.9. This indicated that an increase in body sway perpendicular to the line of shot was associated with a decrease in aim point steadiness. This result is logical, as discussed in the 5s period analysis. The 3s period seems to be the most important for this relationship for R2, with the r value stronger that that returned for the 5s period (r=0.35) and 1s period (r=-0.18). Also, body sway perpendicular to the line of shot seems to influence the aim point steadiness for R2 more than sway parallel to the line of shot based on the larger correlation coefficients (table 5.2.2.2.25).

Figure 5.2.2.2.9: Scattergraph of COPxLength s3 and Std10a0 s3 (z score) for R2.

Of the remaining five shooters, one returned a negative correlation between sway perpendicular to the line of shot and Std10a0 s3 (R5, COPxRange s3, r=-0.37, p=0.11). Another shooter also returned a negative correlation between body sway and Std10a0, but sway parallel to the line of shot was influential in this relationship (R4, COPyRange s3, r=-0.46, p=0.05). This suggests that an increase in body sway is associated with a decrease in aim point steadiness for some shooters, with sway both parallel and perpendicular to the line of shot influential for different shooters.

Std10a0 s3 was also significantly correlated with COPyRange s3 ($r=0.52$, $p=0.02$) for R2, as represented by figure 5.2.2.2.10. This indicated that an increase in sway parallel to the line of shot was associated with an increase in the aim point steadiness of R2. This is another unusual result as the less stable stance, as indicated by an increase in COPyRange s3, might be expected to be associated with a decrease in aim point steadiness. The cause of this relationship is unclear. R2 may have an aim point strategy that is based around body sway in the Y-axis which requires a certain amount of movement for feedback purposes. As such, the more movement, the more feedback, and hence a better Std10a0 score. However, given the small amount of body sway produced by R2, the feedback provided by this movement would be likely to be minimal. As mentioned previously, it may be that an optimal amount of body sway in the Y-axis exists for R2, and reduction of sway below this level is detrimental to performance. It may also be that aim point strategies have affected the aim point data measurement such that what appears to be a fairly strong correlation between COPyRange s3 and Std10a0 s3 is in fact only a reflection of the influence of this strategy on the Std10a0 measurement. While other shooters showed links between Std10a0 s3 and body sway, significant at $p \leq 0.15$ (R4, COPyRange, $r=-0.46$, $p=0.04$, R5, COPxRange, $r=-0.37$, $p=0.11$, R6, COPyLength, $r=-0.34$, $p=0.15$), R2 was the only shooter to show an increase in aim point steadiness with an increase in body sway. This further indicates that this relationship was due to a strategy or trait peculiar to R2. Analysis on a greater number of shots with more thorough analysis of aim point strategies and with gun movement monitored is required to establish a definitive cause for this relationship for R2.

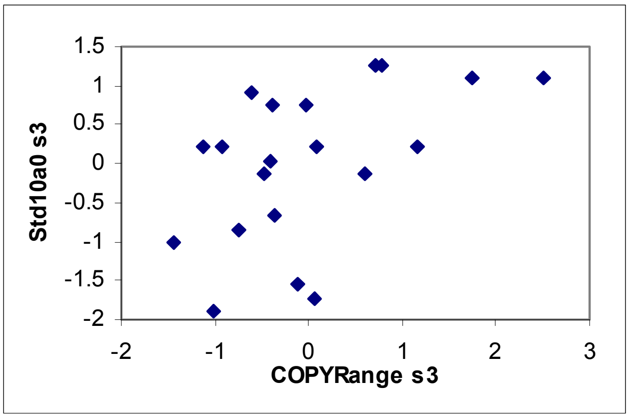


Figure 5.2.2.2.10: Scattergraph of COPyRange s3 and Std10a0 s3 (z score) for R2.

Interestingly, while body sway was related to Std10a0 s3, this relationship was not strong in other time periods. Further, a positive correlation was returned between COPxLength s3 and Std10a0 s3, while a negative correlation was returned between COPyRange s3 and Std10a0 s3. Further, both parameters were included in the best regression predicting Std10a0 from body sway parameters, indicating independent contribution was made by each parameter. This suggests that body sway in the X-axis affects aim point fluctuation differently than body sway in the Y-axis.

Std10.0 s3 was correlated with COPyRange s3 (r=0.38) at p=0.10, indicating that an increase in COPyRange may be associated with an increase in aim point steadiness as measured by Std10.0 s3. This relationship is unusual, as discussed in association with Std10a0 s3. As mentioned, it is possible that an optimal amount of body sway exists for R2 with reduction of sway beyond this level detrimental to performance, as has been mentioned.

However, other shooters did show links between body sway and Std10.0 s3. Strong correlations were returned for R1 between COPxLength s3 and Std10.0 s3 (r=-0.56, p=0.01) and between COPxRange s3 and Std10.0 s3 (r=-0.44, p=0.05). R3 (COPxRange, r=-0.34, p=0.16) and R4 (COPxRange s3, r=-0.42, p=0.07) showed similar links, although these were weaker. These relationships all indicated that an increase in body sway was associated with a decrease in aim point steadiness, as might be expected.

R2 returned a negative correlation between Length s3 and COPyRange s3 (r=-0.47, p=0.04), as represented by figure 5.2.2.2.11. This result indicates that as body sway parallel to the line of shot increased, aim point length decreased for R2. This is an unexpected result. As discussed in the rifle shooting group analysis, a the less stable stance in terms of body sway might more logically be associated with an increase in aim point steadiness and a decrease in aim point length. No other shooter returned a negative correlation between body sway and aim point length in the 3s period. R3 (COPxLength s3, r=0.59, p<0.01 and COPxRange s3, r=0.64, p<0.01), R4 (COPyLength s3, r=0.57, p=0.01 and COPyRange s3, r=0.56, p=0.01) and R6 (COPyLength, r=0.48, p=0.03) all showed strong positive correlations between Length s3 and body sway. These results indicated that as body sway increased, aim point length increased, which is the more expected association. This suggests that this relationship is particular to R2. The causes of this relationship are unclear. As mentioned for the relationship between COPyRange s3 and Std10a0 s3, an optimal amount of body sway may exist for R2. If R2 produces less body sway than this optimal level, aim point fluctuation is increased. Aim point fluctuation will also increase if body sway is greater than this optimal level, as might be suggested by the positive correlation between COPxRange s3 and Std10a0 s3 that was discussed previously in this section. Aim point strategies may also be affecting this correlation.

Or this relationship may reflect a difference between sway in the x and y axes. However, this combination of relationships remains unclear.

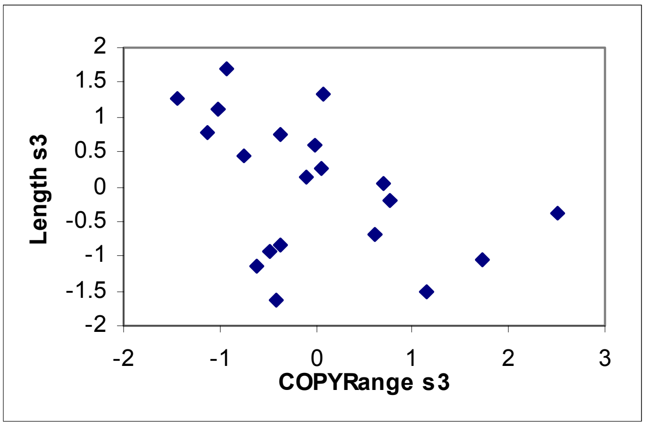


Figure 5.2.2.2.11: Scattergraph of COPyRange s3 and Length s3 (z score) for R2.

LengthX s3 seemed largely unrelated to body sway in the X-axis for R2. However, LengthX s3 may be related to COPyRange s3 (r=-0.30, p=0.20) indicating an increase in body sway parallel to the line of shot (Y-axis) may be associated with a decrease in horizontal aim point length (X-axis). Although this relationship was not strong, this provides another example of an Y-X association, as found in correlations between body sway and error of shot, and is unexpected. However, this relationship may only be indicating the more general relationship between body sway and aim point length for R2, as the correlation between COPyRange s3 and Length was stronger (r=-0.47, p=0.04). Two other shooters also showed Y-X associations between body sway and aim point fluctuation (R4, COPyLength s3, r=0.45, p=0.05 and R6, COPyLength s3, r=0.48, p=0.03), although these were positive correlations, indicating the increase in sway was associated with an increase in aim point length. As for R2, results for R4 and R6 indicate that these relationships may also be of a general nature, as correlations between COPy parameters and Length s3 and between COPy parameters and LengthY s3 were similar or stronger (R4, COPyRange-LengthY, r=-0.46, p=0.05;

R6, COPyLength-LengthY, $r=0.58$, $p<0.01$). An expected relationship was also returned by one shooter, with R3 showing a positive X-X association between body sway and aim point fluctuation (COPxLength s3, $r=0.59$, $p<0.01$ and COPxRange s3, $r=0.64$, $p<0.01$).

LengthY s3 and COPyRange s3 returned a correlation of $r=-0.44$ ($p=0.05$). While the Y-Y association between body sway and aim point fluctuation is logical, the association between an increase in body sway with a decrease in aim point length is not. This may be indicative of the optimal body sway level discussed previously, or aim point strategies influencing measurement. All other shooters showed a relationship significant at $p\leq0.11$ between LengthY s3 and COPy parameters (table 5.2.2.2.26), with only one shooter returning a negative correlation, similar to R2. This suggests that this result is not particular to R2, although it would seem that fewer shooters show this association.

Table 5.2.2.2.26: Summary of correlations between LengthY s3 and body sway parameters for individual shooters (R2 excluded).

	Parameter	r value	p value
R1	COPyRange s3	**0.37**	**0.11**
R3	COPyRange s3	**-0.43**	**0.06**
R4	COPyLength s3	**0.44**	**0.05**
	COPyRange s3	**0.48**	**0.03**
R5	COPyLength s3	**0.63**	**<0.01**
	COPyRange s3	**0.57**	**0.01**
R6	COPyLength s3	**0.58**	**<0.01**
	COPyRange s3	**0.52**	**0.02**
	COPxLength s3	**-0.43**	**0.06**
	COPxRange s3	**-0.66**	**<0.01**

Also of interest from data in table 5.2.2.2.26 is that of R6, who returned strong correlations between all body sway parameters and LengthY s3. While the strongest correlation between COPxRange s3 and LengthY s3 ($r=-0.66$, $p<0.01$) suggests an X-Y association, strong correlations were also returned for both COPy parameters with LengthY s3, supporting the possibility that the relationship indicated is a general, rather than specific one. However, while the correlations between COPy parameters and LengthY s3 are positive, as might be expected, the correlations between COPx parameters and LengthY s3 are negative. Further, both COPyLength and COPxRange were included in the best regression predicting LengthY s3 from body sway parameters ($R=0.71$, $R^2=50.4$, $p<0.01$), indicating both contribute to performance. It is unclear what may have generated this set of relationships for R6. While the 5s period showed similar relationships, all correlations were weaker ($p<0.15$ only) and no relationship existed between LengthY and body sway parameters in the 1s period, indicating that this set of relationships is particular to the 3s period. Further, this was not evident in R2, or any other individual shooter in any period. It may be that these relationships are independent of each other, a fact somewhat indicated in the inclusion of one parameter from each axis in the best regression analysis. It may also be that there is some link between these relationships for R6. However, as this was particular to R6 and not evident in R2 nor in any other shooters, it was considered to be beyond the scope of this study.

Table 5.2.2.2.27 presents the best multiple regression equations for the prediction of aim point parameters from body sway parameters in the 3s period for R2.

Table 5.2.2.2.27: Best multiple regression equations for the prediction of aim point parameters from body sway parameters in the 3s period for R2

	v	R	R^2	p	Cv	Regression Equation
Std10.0 s3	**1**	**0.38**	**14.2**	**0.10**	**-0.4**	51.8 + 38.5 COPyRange s3
Std10a0 s3	**3**	**0.66**	**43**	**0.03**	**3.1**	97.2 - 5.88 COPxLength s3 + 1.82 COPyLength s3 + 13.7 COPyRange s3
LengthX s3	**1**	**0.30**	**9.2**	**0.19**	**-0.6**	32.8 - 5.96 COPyRange s3
LengthY s3	**1**	**0.44**	**19**	**0.05**	**-0.8**	26.4 - 6.04 COPyRange s3

For three of the four aim point parameters, only one body sway parameter was present in the best prediction for R2. As such, no more information is provided than that already presented in the correlation analysis. Body sway parameters accounted for 43.0% of the variance in Std10a0 s3 (p=0.03) with three parameters included. This indicates that almost half of the variance in Std10a0 s3 is accounted for by body sway. Two other shooters, R4 (R=0.46, R^2=21.6, p=0.04) and R5 (R=0.37, R^2=14.0, p=0.10), also showed associations between Std10a0 s3 and body sway, evident in multiple regression analysis.

Strong associations also existed between other aim point parameters and body sway, evident in multiple regression analysis for other shooters, with all individuals returning regressions significant at p<0.05. These analyses are summarised in table 5.2.2.2.28. As can be noted, all shooters are represented in this table. These results suggest that a strong association exists between body sway and aim point fluctuation in the 3s period for rifle shooters. This link is specific to each individual, with different degrees of association and different parameters involved.

Table 5.2.2.2.28: Summary of multiple regression analyses significant at p<0.05 between body sway and aim point parameters in the 3s period for individual shooters (R2 excluded)

	Shooter	R	R^2	p
Std10.0 s3	**R1**	**0.64**	**41.2**	**0.01**
Std10a0 s3	**R4**	**0.46**	**21.6**	**0.04**
LengthX s3	**R3**	**0.72**	**51.8**	**0.01**
	R4	**0.45**	**20.4**	**0.05**
	R6	**0.48**	**23.5**	**0.03**
LengthY s3	**R4**	**0.48**	**23.5**	**0.03**
	R5	**0.68**	**46.6**	**0.01**
	R6	**0.71**	**50.4**	**<0.01**

Table 5.2.2.2.29 reports coefficients from correlations between body sway and aim point parameters in the 1s period for R2 (N=20 shots).

Table 5.2.2.2.29: Correlation Matrix: Coefficients from correlations between body sway and aim point parameters in the 1s period for R2 (N=20 shots)

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s1	**0.16**	**0.09**	**-0.03**	**-0.06**
Std10a0 s1	**-0.21**	**-0.18**	**-0.03**	**0.09**
Length s1	**-0.19**	**-0.27**	**0.27**	**0.04**
LengthX s1	**0.14**	**-0.04**	**0.41**	**0.21**
LengthY s1	**-0.38**	**-0.32**	**-0.06**	**-0.14**

(*p<0.05)

R2 showed no associations between body sway and aim point fluctuation in the 1s period significant at $p<0.05$. The strongest correlation existed between LengthX s1 and COPyLength s1 ($r=0.41$, $p=0.08$), indicated that an increase in body sway parallel to the line of shot may be associated with an increase in horizontal aim point fluctuation on target. As discussed previously, while the association of increased body sway with increased aim point length is logical, the Y-X association is not. It is unclear what might be generating this relationship between axes, although possible mechanisms have been discussed previously. This result was not specific to R2, with one other shooter, R5, showing a similar relationship (COPyLength s1, $r=0.46$, $p=0.04$ and COPyRange s1, $r=0.54$, $p=0.01$). However, R5 returned very strong correlations between sway in the Y-axis and LengthY s1 (R5, COPyLength s1, $r=0.77$, $p<0.01$ and COPyRange, $r=0.74$, $p<0.01$), suggesting that the relationship between COPy parameters and LengthX s1 may be indicating that increased body sway was associated with increased aim point fluctuation generally, rather than a specific Y-X relationship for this shooter. A similar relationship was not evident for R2, suggesting that the relationship between LengthX s1 and COPyLength s1 for R2 may be indicating this specific Y-X association.

R2 also showed X-Y associations between LengthY s1 and COPxLength ($r=-0.38$, $p=0.10$) and between LengthY s1 and COPxRange s1 ($r=-0.32$, $p=0.18$) although these relationships were not particularly strong. These indicated that an increase in body sway perpendicular to the line of shot may be associated with a decrease in aim point fluctuation in the Y-axis on target. Two other shooters showed a relationship between COPx parameters and LengthY s1 (R4, COPxLength s1, $r=0.50$, $p<0.05$ and R5, COPxLength s1, $r=0.44$, $p=0.05$). Also, two other shooters showed an increase in aim point length with a decrease in body sway (R3, COPyRange s1, $r=-0.35$, $p=0.15$ and R6, COPyRange s1, $r=-0.35$, $p=0.15$), although, as for R2, these relationships were not particularly strong. These results suggest that the unexpected relationships found for R2 are not specific to that shooter, although the combination of a negative correlation and the X-Y association between body sway and aim point fluctuation was. The possible causes of this relationship have been discussed in the 3s and 5s period analyses.

Strong relationships were also shown between COPy parameters and LengthY s1 for two other shooters (R4, COPyLength s1, $r=0.53$, $p=0.02$ and COPyRange s1, $r=0.50$, $p=0.02$ and R5, COPyLength s1, $r=0.77$, $p<0.01$ and COPyRange s1, $r=0.74$, $p=<0.01$). This indicated that for some shooters, an increase in body sway parallel to the line of shot was strongly associated with an increase in aim point fluctuation vertically on target. This is an expected result, with the positive correlations and Y-Y association between body sway and aim point fluctuation both logical links.

Overall, then, the relationship between body sway parameters and LengthY s1 evident in all shooters tested. Further, these relationships encompassed positive and negative correlations as well as Y-Y, X-Y and Y-X associations. This highlights the need for individual analysis at the elite level of rifle shooting.

R2 showed only very weak relationships between Std measures and body sway parameters and between Length and body sway parameters in the 1s period. However, this was not the case for the group as a whole. Table 5.2.2.2.30 summarises the relationships between body sway parameters and Std measures, and between body sway parameters and Length, in the 1s period, significant at $p<0.05$ for other shooters. Interestingly, while both R1 and R4 returned positive correlations between body sway and aim point fluctuation, R5 returned a negative correlation. This suggests that body sway is related to aim point fluctuation in the 1s period for some shooters, and this association is specific to the individual, with the direction of association different for different shooters

Table 5.2.2.2.30: Summary of correlations between Std10.0 s1, Std10a0s1, Length s1 and body sway parameters for individual shooters (R2 excluded)

	Shooter	Parameter	r	p
Std10.0 s1	R5	**COPyLength s1**	**-0.48**	**0.03**
		COPyRange s1	**-0.47**	**0.03**
Std10a0 s1	R1	**COPxRange s1**	**0.52**	**0.02**
	R5	**COPyLength s1**	**-0.67**	**<0.01**
Length s1	R4	**COPyLength s1**	**0.59**	**<0.01**
	R5	**COPyLength s1**	**0.64**	**<0.01**
		COPyRange s1	**0.54**	**0.01**

Table 5.2.2.2.31 presents the best multiple regression equations for the prediction of aim point parameters from body sway parameters in the 1s period for R2.

Table 5.2.2.2.31: Best multiple regression equations for the prediction of aim point parameters from body sway parameters in the 1s period for R2

	v	R	R^2	p	Cv	Regression Equation
Std10.0 s1	**1**	**0.16**	**2.6**	**0.50**	**-0.9**	75.7 + 9.3 COPxLength s1
Std10a0 s1	**1**	**0.20**	**4.2**	**0.39**	**-0.3**	101 - 1.63 COPxLength s1
LengthX s1	**1**	**0.41**	**16.9**	**0.07**	**0**	6.98 + 1.26 COPyLength s1
LengthY s1	**1**	**0.38**	**14.8**	**0.09**	**-0.2**	9.48 - 1.68 COPxLength s1

No more information was provided by multiple regression analysis for R2, with only one body sway parameter present in the regression equation for all aim point variables (Table 5.2.2.2.31).

However, in four of the remaining five shooters (R3, R4, R5, R6), multiple regression analysis did provide more information than that gained from correlations, with combinations of body sway parameters better predicting aim point variables at $p<0.05$ (Appendix F). This indicates that aim point fluctuation and body sway are related for some shooters. Further, this relationship is strong and accounts for a large amount of the variance in aim point parameters. Results of the strongest multiple regression analysis for each of these four shooters is presented in table 5.2.2.2.32.

Table 5.2.2.2.32: Strongest regressions between body sway and aim point parameters in the 1s period for R3, R4, R5 and R6.

	Aim point parameter	R	R^2	p
R3	LengthY s1	**0.63**	**40.3**	**0.13**
R4	Std10.0 s1	**0.79**	**62.8**	**<0.01**
R5	LengthY s1	**0.79**	**62.3**	**<0.01**
R6	LengthX s1	**0.62**	**39.0**	**0.04**

Overall, these results indicate that there are strong associations between body sway and aim point fluctuation in the 1s period before shot for some rifle shooters. These relationships varied in degree of association, direction of association and the body sway and aim point parameters that were associated for different shooters. This indicates that analysis on an individual basis is important in any research with elite level standing rifle shooting.

Further, a number of relationships were unusual. An increase in body sway was associated with a decrease in aim point fluctuation for some shooters. Also, some shooters showed X-Y and Y-X associations between body sway and aim point fluctuation. More research is required to better define these unusual relationships and to discern the mechanism for the X-Y and Y-X associations.

In summary, the 3s period seemed to be the period of most interest for R2, as the three significant correlations between body sway and aim point fluctuation were generated from this period. Further, r values were generally larger than for those in the 5s and 1s periods. However, while an increased sway perpendicular to the line of shot seems to be associated with a decrease in aim point steadiness, the opposite was the case with sway parallel to the line of shot for R2 in this period. The cause of this relationship is unclear, although a number of possibilities exist. It is possible that an optimal amount of sway exists for R2, over or under which aim point fluctuation is increased. It may be that in attempting to accommodate the aim point fluctuation that might be generated in the X-axis on target by sway in the X-axis, aim point fluctuation is generated in the Y-axis. Similarly, in attempting to accommodate the aim point fluctuation that might be generated in the Y-axis on target by sway in the Y-axis, aim point fluctuation is generated in the X-axis. It may also be that aim point strategies are affecting the analysis. Further research with upper body and gun movement quantified and with aim point strategies accounted for is required to better define this relationship for R2. Further, a shot by shot analysis will also be useful in defining this relationship more thoroughly.

As mentioned in the rifle shooting group section, the analysis of X-Y and Y-X association was perhaps naive. The theoretical framework behind a relationship between these two factors is poor, with any relationship between measures in the two axes suggesting that another variable is associated with the problem that generates this relationship. Body sway parallel to the line of shot (Y-axis), with no upper body adjustment, will move the aim point vertically on the target (Y-axis). Likewise, body sway perpendicular to the line of shot (X-axis) will move the aim point horizontally on target (X-axis). As such, for an X-Y or a Y-X association to exist, other movements, not measured in this study, must be involved. This being the case, body sway may be related to this upper body movement, but cannot cause the X-Y or Y-X association directly. So it is this upper body movement that causes the aim point vertical movement, rather than the body sway.

With the individual variation found throughout this analysis, research in the elite rifle shooting area requires an individual analysis component to extract important information from the data and avoid group based data loss. Further, this variation seemed to extend to a shot to shot basis for individual shooters, indicating that this level of analysis may also be useful. It might be expected that elite level shooters will make adjustments from shot to shot, based on perceived errors from previous shots. This will influence statistical analysis, as some important factors may be evident for some shots but not others. Any analysis over a number of shots, then, may not detect these factors.

5.2.3 Pistol Shooters: relationship between body sway, aim point fluctuation and performance

Repeating for clarity, the examination of pistol shooters was reduced to only the 1s period, due to the short Aim Time (4.2s) returned, which influenced body sway and aim point data in the 5s and 3s periods. As only the 1s period was analysed, parameters have been reported without the corresponding time period.

5.2.3.1 Pistol: Group Analysis

5.2.3.1.1 Shooting performance for the pistol shooting group

Table 5.2.3.1.1 reports mean values for shooting performance and aim time for the pistol shooting group (N=5).

Table 5.2.3.1.1: Shooting performance for the pistol shooting group (N=5)

		Mean	*SD*
Result	score (max 10.9)	**9.73**	***0.35***
PosX	horizontal distance to centre of target (mm)	**6.7**	***2.6***
PosY	vertical distance to centre of target (mm)	**5.9**	***1.5***
Aim Time	time of aim point on target (s)	**4.2**	***2.0***

The mean Result achieved by the pistol-shooting group was 9.73 (out of a possible 10.9). This value is slightly smaller than the rifle shooting group (10.09) and is typical of competition scores in elite pistol shooting. The mean PosX value for the group was 6.7mm, while PosY averaged 5.9mm, indicating more error of shot occurs in the horizontal axis. These values are both larger than the rifle shooting group values (PosX=1.6mm, PosY=1.1mm), but smaller than the 7.0mm and 8.7mm, for horizontal and vertical axes respectively, found by Mason *et al.* (1990) for elite pistol shooters. Interestingly, error in the vertical axis was greater than the horizontal axis in the Mason *et al.* study.

The mean Aim Time was 4.2 seconds. This time is much shorter than the rifle shooting group (11.3s) and slightly shorter than the aim time of 5.2s reported by Mason *et al.* (1990). As mentioned previously, this short time prompted the reduction of analysis for pistol shooters to only the 1s period.

5.2.3.1.2 Body sway measures and relationship with shooting performance for the pistol shooting group.

Table 5.2.3.1.2 details the mean values for body sway parameters for the 1s period prior to shot (N=5).

Table 5.2.3.1.2: Mean body sway values for the pistol shooting group (N=5)

	Mean	*SD*
COPxLength (mm)	**3.01**	***1.03***
COPxRange (mm)	**1.89**	***0.34***
COPyLength (mm)	**2.33**	***0.53***
COPyRange (mm)	**0.96**	***0.20***

The mean ranges of COP movement in the last second were 1.89mm and 0.96mm for COPx and COPy respectively. These values are smaller than the COPxRange of 3.3mm and COPyRange of 3.1mm found by Mason *et al.* (1990) for similar level (elite) shooters. This study's COP range values were also smaller than those reported for non-shooters which have been reported as low as 3mm (Ekdahl *et al.*, 1989) and up to 16mm (Simoneau *et al.*, 1992).

COPxRange was larger than COPyRange for the pistol-shooting group, indicating more range of body sway is produced perpendicular to rather than parallel to the line of shot. This was similar to the findings in both the rifle group and the Mason *et al.* (1990) study. This result seems reasonable, given the movement in COPx is predominantly AP sway, which has been found to be larger than ML sway in shooters (eg. Niinimaa and McEvoy, 1983; Dillman, 1983) and in non-shooters (eg. Ekdahl *et al.*, 1989; Murray *et al.*, 1976).

Average COPxLength for the pistol-shooting group was 3.01mm, while the average COPyLength value was 2.33mm. No comparison data exists for COP lengths in pistol shooting. The values are slightly larger than the rifle shooting group (COPxLength s1=1.81mm, COPyLength s1=2.16mm). However, unlike the rifle-shooting group, COPx lengths were larger than COPy lengths. This difference indicates a posture control difference between the disciplines. There are a number of differences between pistol and rifle shooting which may contribute to this difference, such as the different clothing worn and the different gun hold positions adopted by each.

As mentioned previously, all body sway values returned by the pistol-shooting group were larger than for the corresponding parameters measured for the rifle-shooting group (table 5.2.2.1.2). This increased body sway is likely to be, in part, due to the different clothing worn by the two disciplines. Rifle shooters wear stiff leather clothing and robust boots, which would assist in reducing body sway. Pistol shooters have no special clothing. Aalto *et al.* (1990) report a significant reduction in body sway when rifle shooters wore this special clothing, compared to when the shooters wore street clothing, such as jeans, shirt and running shoes. Aalto *et al.* also report that the rifle shooters were found to be more stable than pistol shooters even in the street clothing condition, suggesting a better control of sway. This may be a reflection of the requirements of the different disciplines, as rifle shooting targets are 3.4 times smaller than pistol shooting targets, this increased sway control may be necessary.

Results from correlations between body sway parameters and performance for the pistol shooting group are reported in table 5.2.3.1.3 (N=5).

Table 5.2.3.1.3: Correlation Matrix: Coefficients from correlations between body sway parameters and shot performance for the pistol shooting group (N=5)

	Result	PosX	PosY
COPxLength	**-0.14**	**-0.25**	**0.66**
COPxRange	**-0.41**	**0.10**	**0.80**
COPyLength	**0.55**	**-0.82**	**-0.09**
COPyRange	**0.42**	**-0.74**	**0.07**

No relationship was evident for correlations between body sway parameters and Result for the pistol-shooting group, significant at $p<0.30$. This suggests that body sway and shooting performance are not strongly associated for this elite group of pistol shooters, although with only five shooters, a coefficient of $r\geq0.88$ is required for statistical significance at $p\leq0.05$. This does not support the findings of Mason *et al.* (1990) nor Iskra *et al.* (1989) but is in agreement with the comments of Aalto *et al.* (1990) who suggested that body sway was less important than other skill factors for pistol shooting. The scattergraph of COPxLength and Result (figure 5.2.3.1.1) was typical of the relationships between body sway and Result, with three shooters clustered together. The remaining two shooters were distinctive, with one (P4) showing similar body sway values to the cluster but a much poorer Result, while the other shooter (P1) showed a similar Result to the cluster, but much larger body sway values. These shooters influenced correlations considerably.

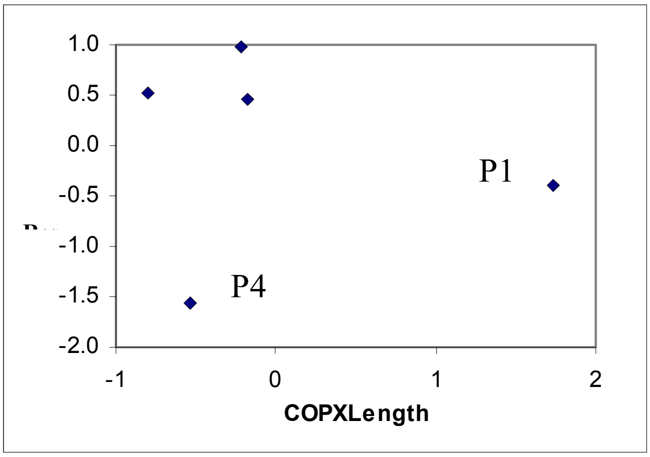


Figure 5.2.3.1.1: Scattergraph of COPxLength and Result (z scores) for the pistol shooting group.

It can be noted from figure 5.2.3.1.1, that with P4 eliminated, a more obvious relationship is evident among the remaining shooters, with the correlation strengthening to r=-0.85 (p=0.15). COPxRange also showed a stronger relationship with Result (r=-0.74 with P4 eliminated) although this relationship is significant only at p=0.25. Both relationships indicate that an increase in body sway perpendicular to the line of shot may be associated with a decrease in performance. This is a logical result and was evident in the rifle-shooting group and individual analyses, as an increase in body sway will increase gun and possibly aim point movement, which might be expected to be associated with decreased performance. COPy parameters showed no association with Result with P4 eliminated.

With P4 included and P1 eliminated, no relationship is evident between Result and COPxLength (r=0.30, p=0.70) and between Result and COPxRange (r=0.39, p=0.61). However, as evident in figures 5.2.3.2.2 and 5.2.3.2.3, an association did exist for the remaining four shooters between Result and COPyLength (r=0.93, p=0.07) and between Result and COPyRange (r=0.93, p=0.07). These positive correlations indicated, unexpectedly, that an increase in body sway parallel to the line of shot was associated with an increase in performance. A similar result was found for some rifle shooters. As discussed, it may be that an optimal amount of body sway exists for these pistol shooters and further reduction of this sway is detrimental to performance, or that performance feedback is gained from body sway (although this seems unlikely, as discussed in section 5.2.2.1).

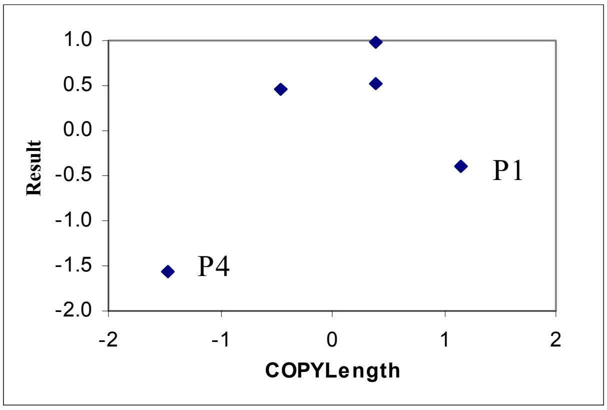


Figure 5.2.3.1.2: Scattergraph of COPyLength and Result (z scores) for the pistol shooting group.

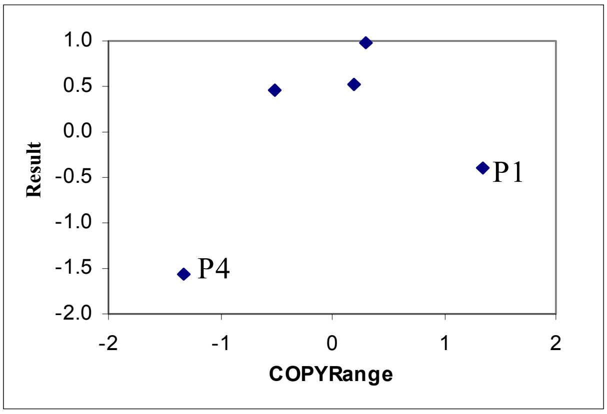


Figure 5.2.3.1.3: Scattergraph of COPyRange and Result (z scores) for the pistol shooting group.

Stronger correlations were returned between body sway parameters and error of shot on target, as measured by PosX and PosY. The relationship between COPyLength and PosX ($r=-0.82$, $p=0.09$) and between COPyRange and PosX ($r=-0.74$, $p=0.16$), indicated that an increase in body sway parallel to the line of shot may be associated with a decrease in the horizontal errors in shot on target. This is a surprising result, as an increase in body sway might be expected to be associated with an increase, rather than a decrease, in shot errors. It may be that an optimal level of body sway exists for pistol shooters and further reduction of this sway is detrimental to performance. Also surprising in this relationship was the Y-X association between body sway parallel to the line of shot and error of shot in the horizontal axis on target. Similar associations were evident in rifle analyses. It may be that COPy parameters are general indicators of body sway, while PosX is a general indicator of performance for the pistol-shooting group. As such, this relationship simply indicates that body sway is associated with the error of shot on target. It was also considered that a technical aspect of pistol shooting exists, whereby as body sway parallel to the line of shot increases (as measured by COPy parameters), aim point fluctuation in the horizontal axis increases which in turn increases the horizontal error of shot on target. This was later discounted as COPy parameters and LengthX did not show a particularly strong association (table 5.2.3.1.9). It may be that some feedback is gained from body sway in one axis that assists at the point of shot in the vertical axis on target. It may also be that in accommodating the Y-axis gun movement (and corresponding aim point movement) that will be produced by body sway in the Y-axis, these shooters generate gun movement which leads to aim point fluctuation in the X-axis on target. As discussed previously, there must be another factor that exists between body sway in the Y-axis and aim point error in the X-axis for this relationship to exist, such as upper body or gun adjustment.

However, as can be noted in figures 5.2.3.1.4 and 5.2.3.1.5, these correlations were influenced strongly by P4. With P4 removed, the correlation between COPyLength and PosX weakened from r=-0.82 to r=-0.01. The correlation between COPyRange and PosX also weakened from r=-0.74 to r=-0.09. Both indicated that no relationship between the variables existed without P4. P1 showed no distinction from the remaining shooters in these relationships.

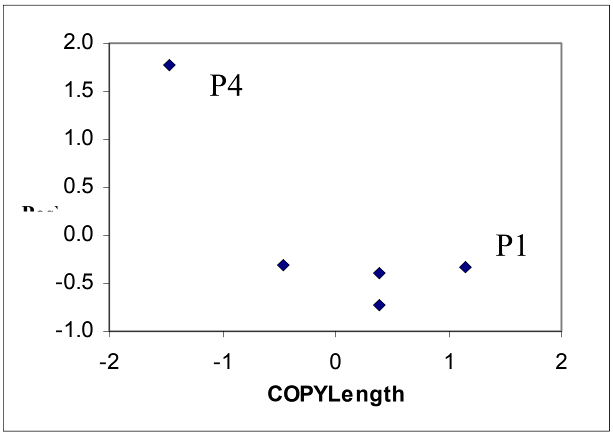


Figure 5.2.3.1.4: Scattergraph of COPyLength and PosX (z scores) for the pistol shooting group.

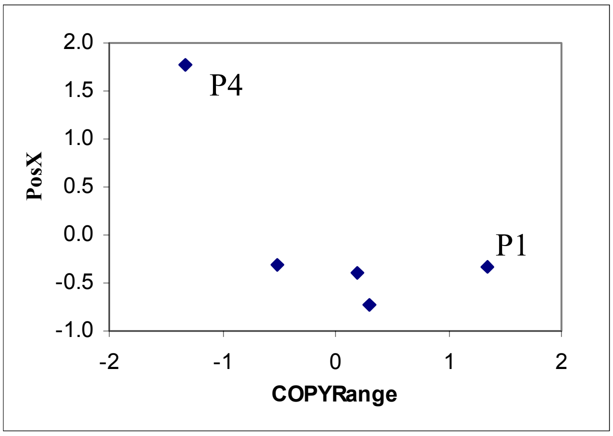


Figure 5.2.3.1.5: Scattergraph of COPyRange and PosX (z scores) for the pistol shooting group.

The correlation between COPxRange and PosY (r=0.80, p=0.10) indicated that an increase in sway perpendicular to the line of shot may be associated with an increase in error of shot in the vertical axis on target (figure 5.2.3.1.6). While the association between increased body sway and increased error of shot is expected and logical, the X-Y association is not. This ‘crossover’ was evident also between COPy and PosX for the pistol-shooting group as well as for the rifle-shooting group and individuals. The same discussion points are also relevant for this relationship. No relationship was evident between COPxRange and LengthY (table 5.2.3.1.9), indicating that this was not the mechanism for generating this X-Y relationship. The cause of both relationships remains unclear.

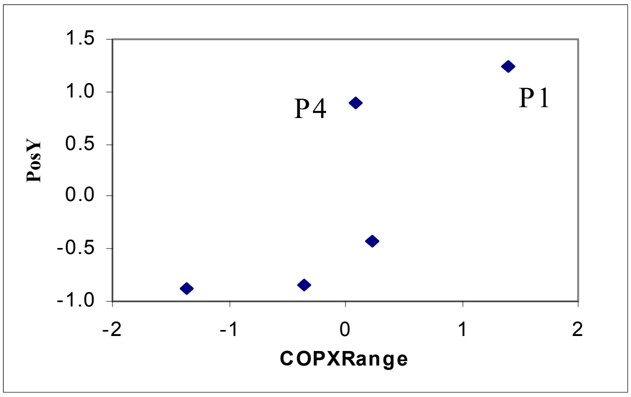


Figure 5.2.3.1.6: Scattergraph of COPxRange and PosY (z scores) for the pistol shooting group.

As is evident from figure 5.2.3.1.6, P4 did not influence this data greatly, and when eliminated there was an increase in the r value for the correlation with no change in the significance level for this relationship (r=0.80, p=0.10 to r=0.90, p=0.10). However, P1 did influence the result, with the relationship weakening to r=0.58 (p=0.42) when removed. While the relationship between sway in the X-axis and error in the Y-axis may still exist, as indicated by a coefficient of r=0.58, it is significant only at p=0.42. As such, more research with a greater N is required to substantiate the relationship. It should be noted, though, that neither P1 nor P4 would have been brought into question from this scattergraph alone.

COPy parameters showed no association with PosY for the pistol group. This indicates that factors other than body sway influence error in the Y-axis on target. However, as can be noted from figures 5.2.3.1.7 and 5.2.3.1.8, P1 and P4 exerted considerable influence on these results. The elimination of P4 strengthened the relationship between PosY and COPyLength from r=-0.09 (p=0.89) to r=0.65 (p=0.35) and between PosY and COPyRange from r=0.07 (p=0.91) to r=0.77 (p=0.23). Both relationships indicated that an increase in sway parallel to the line of shot was associated with an increase in error in the Y-axis. These are both expected result, although with only four shooters used, these relationships are significant at p=0.35 and p=0.23, as reported. Interestingly, a negative correlation was returned when P4 was included and P1 was eliminated between PosY and COPyLength from r=-0.09 (p=0.89) to r=-0.97 (p=0.03) and between PosY and COPyRange from r=0.07 (p=0.91) to r=-0.97 (p=0.03). These relationships indicated an increase in sway parallel to the line of shot was associated with a decrease in error in the vertical axis on target. This is an unexpected relationship, discussed previously, as an increase in body would be more logically associated with an increase in error. If this is in fact the case for pistol shooters, it may be that an optimal level of sway control is required for good performance, but further reduction of this sway is detrimental to performance.

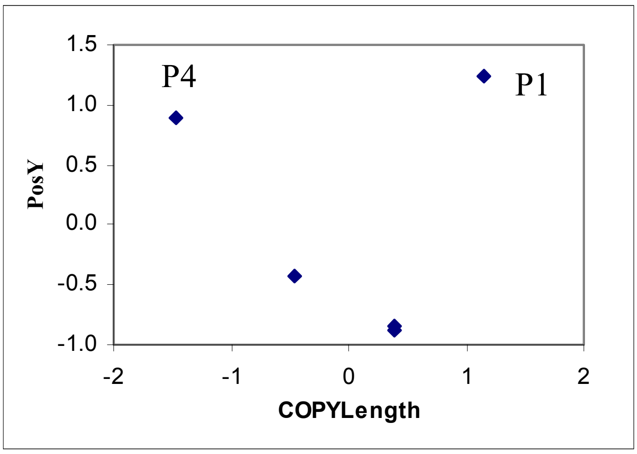


Figure 5.2.3.1.7: Scattergraph of COPyLength and PosY (z scores) for the pistol shooting group.

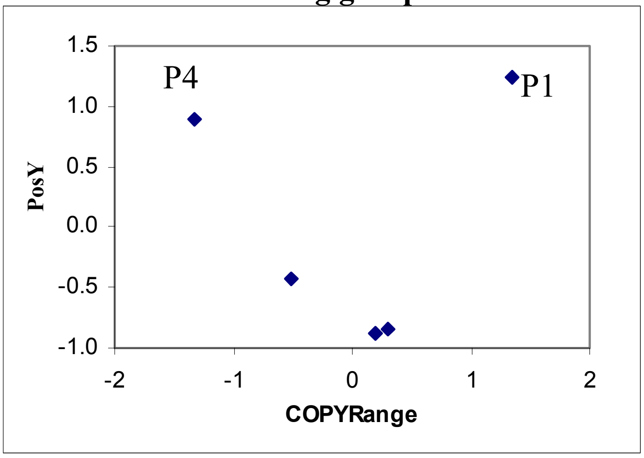


Figure 5.2.3.1.8: Scattergraph of COPyRange and PosY (z scores) for the pistol shooting group.

Table 5.2.3.1.4 summarises the effect of P4 and P1 on correlations between body sway parameters and performance for the pistol-shooting group.

Table 5.2.3.1.4: Comparison of correlations between body sway parameters and performance for the pistol shooting group with and without P1 and P4

	Result			PosX			PosY		
	Group	*-P4*	-P1	Group	*-P4*	-P1	Group	*-P4*	-P1
COPxLength	**-0.14**	***-0.85***	0.30	**-0.25**	***0.27***	-0.28	**0.66**	***0.98***	-0.08
COPxRange	**-0.41**	***-0.74***	-0.39	**0.10**	***0.31***	0.41	**0.80**	***0.90***	0.58
COPyLength	**0.55**	***-0.57***	0.93	**-0.82**	***-0.09***	-0.93	**-0.09**	***0.65***	-0.97
COPyRange	**0.42**	***-0.67***	0.93	**-0.74**	***-0.01***	-0.92	**0.07**	***0.77***	-0.97

-P4 refers to the correlation using data from only 4 shooters with P4 eliminated (N=4)
-P1 refers to the correlation using data from only 4 shooters with P1 eliminated (N=4)

In summary, the relationship between body sway and performance in pistol shooting is unclear from this data. With two shooters, P1 and P4, influencing the data strongly, correlations have a low confidence level. The group of five shooters tested may represent the normal distribution of elite pistol shooters, in which case, body sway is not strongly related to Result. This would suggest that body sway is does not discern between pistol shooters as a performance indicator and supports the suggestion of Aalto *et al.* (1990) that body sway is less important to pistol shooting performance than other skills. However, some influence is evident between body sway and error of shot. Specifically, and rather unusually, an increase in sway perpendicular to the line of shot was linked with an increase in vertical error of shot (X-Y), while an increase in sway parallel to the line of shot was associated with a decrease in the horizontal error (Y-X). Similar relationships were evident in rifle analyses. Other movements, such as upper body and gun adjustments, must be involved for this result to occur.

However, P1 and P4 may be ‘outlying’ from the normal distribution of elite pistol shooters. With P1 eliminated, the data indicated that an increase in body sway parallel to the line of shot was associated with an increase in Result and a decrease in error of shot in the vertical axis. These relationships were surprising, as an increase in sway might be expected to be associated with a decrease in performance. An optimal amount of body sway may exist and further reduction of this sway will lead to a decrease in performance. More expected results were generated when P4 was eliminated, although these did not seem to be particularly strong. These relationships indicated that an increase in body sway parallel to the line of shot was associated with a decrease in performance and an increase in sway perpendicular to the line of shot was associated with an increase in error in the Y-axis on target.

This dataset of pistol shooters is sensitive to single datapoints, due to the low number of shooters and the elite nature of the group. This sensitivity has made conclusions difficult to draw from the data as, while a number of possibilities exist in this data, these possibilities include almost all the possibilities that could exist. This assessment requires more research with a larger number of elite level pistol shooters to better define the relationship between body sway and performance on a group basis.

5.2.3.1.3 Aim point measures and relationship with shooting performance for the pistol shooting group

Table 5.2.3.1.5 details mean values for aim point parameters measured over 1s for the pistol shooting group (N=5).

Table 5.2.3.1.5: Mean aim point values for the pistol shooting group (N=5)

		Mean	SD
Std10.0	% time	**42.1**	**11.2**
Std10a0	% time	**65.2**	**8.0**
Length	mm	**114.9**	**19.3**
LengthX	mm	**76.1**	**11.1**
LengthY	mm	**70.7**	**15.1**

Aim point data for the pistol shooting group showed a mean Std10.0 value of 42.05% in the last second before shot, indicating less than half of the aim point fluctuation remained inside the 10 ring during this time. The mean Std10a0 value of 65.17% was larger than the Std10.0 value, indicating that the aim point centred on a point outside the centre of the target. As mentioned previously, Std10.0 can never be larger than Std10a0. Both were smaller than the rifle shooting group (Std10.0 s1=72.1% and Std10a0 s1=88.4%). No comparison data exists in the literature for this parameter.

Mean group Length (114.9mm), LengthX (76.1mm) and LengthY (70.7mm) were all larger than aim point lengths for the rifle shooting group in the 1s period (Length=16.0mm, LengthX=11.9mm, LengthY=8.3mm). However, these values were smaller than the 155.8mm, 108.9mm and 89.2mm for Length, LengthX and LengthY found by Mason *et al.* (1990) for a similar level group of pistol shooters. There is no obvious reason why this difference occurred, nor is there other comparison data in the literature to assess if this difference might be reasonably expected. In both studies, aim point length was larger in the X-axis (horizontal), indicating greater aim point fluctuation in this axis, compared with the Y (vertical) axis. This was also the case with rifle shooters in this study.

The difference between pistol and rifle aim point fluctuation is not surprising, given the comparative gun holding positions. The gun hold for pistol shooters involves the use of only one arm, which is extended horizontally in front of the body. Rifle shooters adopt a double hold position (both arms) and the gun can be locked into the chest, shoulder and arm. Further, many rifle shooters adopt the most compact and stable upper body position possible, interlocking body parts, such as pressing the front elbow into the side of the trunk. This effectively reduces the degrees of freedom of the body/gun system. The pistol shooting position is less stable, with more joints and segments able to move, allowing greater movement of the gun and therefore aim point. Aim time may relate to this position also. Rifle shooters are able to efficiently hold the same position for longer periods. Pistol shooters, relying more on muscular contraction about the upper arm to hold the gun stable may not be able to maintain this hold position for long periods of time without muscular fatigue and tremor becoming a factor in the quality of the hold. The supportive clothing worn by rifle shooters may also assist in stabilising the gun and, as a result, the aim point, although no studies have examined this.

The correlation matrix between aim point parameters and shooting performance for the pistol shooting group is detailed in table 5.2.3.1.6 (N=5).

Table 5.2.3.1.6: Correlation Matrix: Coefficients from correlations between aim point parameters and performance for the pistol shooting group (N=5)

	Result	PosX	PosY
Std10.0	**0.95***	**-0.99****	**-0.64**
Std10a0	**0.66**	**-0.85**	**-0.29**
Length	**-0.71**	**0.81**	**0.49**
LengthX	**-0.48**	**0.56**	**0.40**
LengthY	**-0.84**	**0.94***	**0.53**

(* p<0.05, ** p<0.01)

Result was positively correlated with Std10.0 (r=0.95, p=0.02) for the pistol group. This indicated that an increased aim point steadiness, as measured by the percentage time spent inside the 10 ring, was associated with an increase in Result. This is a logical link, as discussed in the rifle shooting group section (5.2.2.1.3). Repeating, the longer the aim point remains inside the 10 ring, the greater the chance of the point of trigger coinciding with the aim point being located on a 10 or above scoring position on target and improving performance. As can be noted in figure 5.2.3.1.9, a strong correlation is evident between all shooters. As was the case in the body sway-performance relationships for the pistol group, one shooter (P4) seemed to be distinct from the remaining shooters. However, when P4 was removed, the correlation strengthened to r=0.99 (p<0.01). This indicated that a strong relationship between Std10.0 and Result existed for pistol shooters in this study.

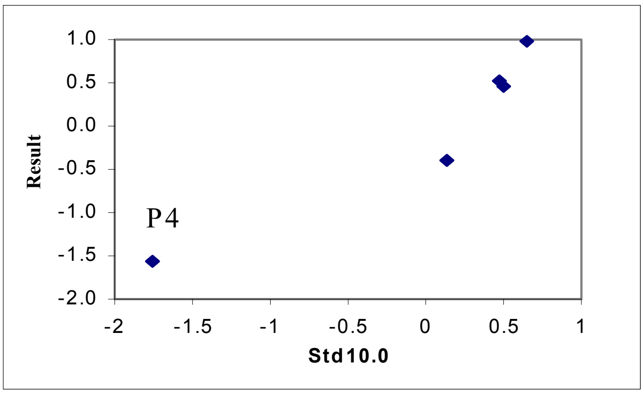


Figure 5.2.3.1.9: Scattergraph of Std10.0 and Result (z scores) for the pistol shooting group.

Negative correlations between Result and Length (r=-0.71, p=0.18) and Result and LengthY (r=-0.84, p=0.08) indicated that an increase in aim point length may be associated with a decrease in result for the pistol shooting group. Once again P4 influenced these correlations. However, in contrast to the relationship between Std10.0 and Result for the pistol-shooting group, without P4, no relationship was evident (see figures 5.2.3.1.10 and 5.2.3.1.11). The coefficients for correlations when P4 was removed from the data set dropped to r=0.21 (p=0.79) for the correlation between Length and Result and to r=0.10 (p=0.89) for the correlation between LengthY and Result. This indicated that no relationship existed between these parameters for the remaining four pistol shooters.

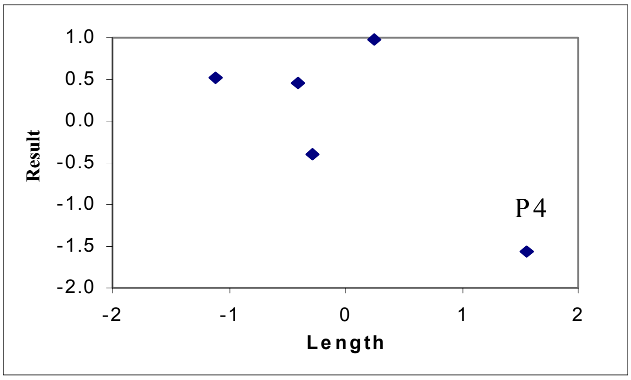


Figure 5.2.3.1.10: Scattergraph of Length and Result (z scores) for the pistol shooting group.

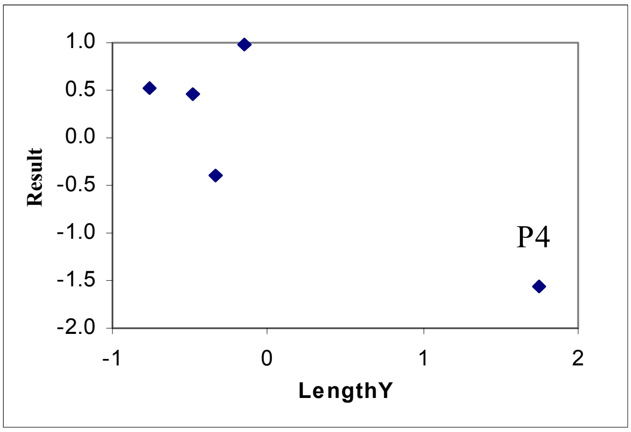


Figure 5.2.3.1.11: Scattergraph of LengthY and Result (z scores) for the pistol shooting group.

Correlations between aim point parameters and PosX all returned reasonably strong r values (table 5.2.3.1.6). PosX was negatively correlated with Std10.0 (r=-0.99, p<0.01). This indicated that a greater aim point steadiness was associated with a decrease in errors in the X-axis on target. This is an expected and logical result, and was evident also in rifle group and individual analyses. Repeating, the longer time spent inside the 10.0 ring increasing the chances of scoring 10 or above, as well as indicating greater aim point control, both of which might be expected to reduce errors of shot. This relationship was influenced considerably by P4, as can be noted in figure 5.2.3.1.12, which was typical of the correlations between aim point parameters and PosX. When P4 was removed from the analysis the r value dropped to r=-0.65 (p=0.35). While the relationship still returned a reasonable correlation coefficient and remained negative, the result is significant only at p=0.35. More work with larger numbers of pistol shooters would be required to substantiate this relationship.

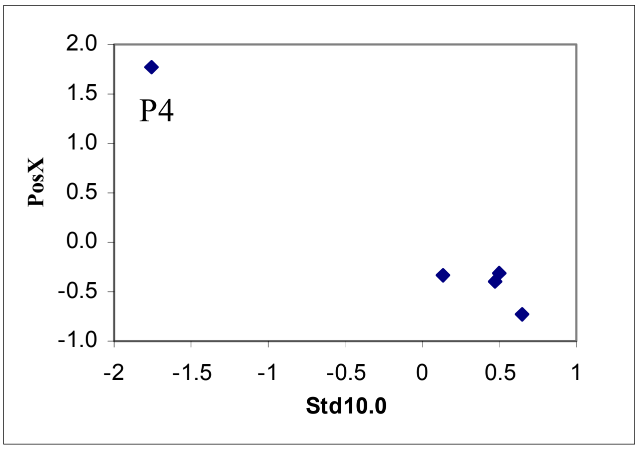


Figure 5.2.3.1.12: Scattergraph of Std10.0 and PosX (z scores) for the pistol shooting group.

The relationship between Std10a0 and performance was of particular note in the pistol-shooting group statistical analysis. A marked difference was evident in these relationships with and without P4. Std10a0 and Result (r=0.66, p=0.23 to r=-0.79, p=0.22) and Std10a0 and PosX (r=-0.85, p=0.07 to r=0.98, p=0.02) both showed a change in the direction of the relationship between parameters when P4 was eliminated. This can be seen graphically in figures 5.2.3.1.13 and 5.2.3.1.14, with four shooters (P4 eliminated) showing a relationship that is in the opposite direction to that indicated with all five shooters included. These relationships indicated an increase in aim point steadiness may be associated with an increase in Result and a decrease in errors in the horizontal axis on target. This surprising relationship was also evident in rifle analyses and discussed in more detail in those sections (5.2.2.1 and 5.2.2.2). It may be that an optimal amount of body sway exists for these four shooters, or that aim point strategies have influenced these results.

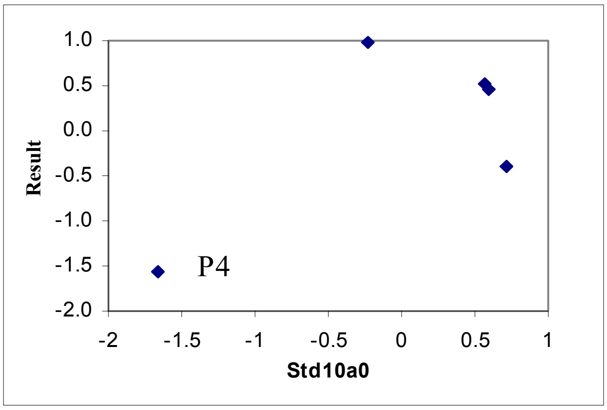


Figure 5.2.3.1.13: Scattergraph of Std10a0 and Result (z scores) for the pistol shooting group.

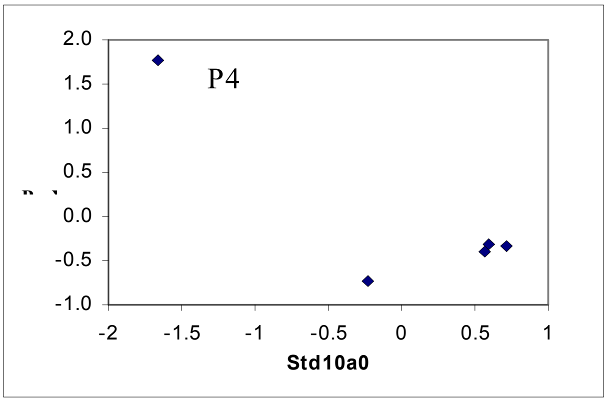


Figure 5.2.3.1.14: Scattergraph of Std10a0 and PosX (z scores) for the pistol shooting group.

Table 5.2.3.1.7 summarises the effect of P4 on correlations between aim point parameters and performance (Result and PosX) for the pistol-shooting group.

Table 5.2.3.1.7: Comparison of correlations between aim point parameters and performance (Result, PosX) for the pistol shooting group with and without P4

	Result		PosX	
	Group	*-P4*	Group	*-P4*
Std10.0	**0.95**	***0.99***	**-0.99**	***-0.65***
Std10a0	**0.66**	***-0.79***	**-0.85**	***0.98***
Length	**-0.71**	***0.21***	**0.81**	***-0.65***
LengthX	**-0.48**	***0.24***	**0.56**	***-0.66***
LengthY	**-0.84**	***0.10***	**0.94**	***-0.62***

-P4 refers to the correlation using data from only 4 shooters with P4 eliminated (N=4)

Correlations between PosY and aim point parameters indicated a slightly different relationship for the pistol-shooting group. The correlation between Std10.0 and PosY, as represented in figure 5.2.3.1.15, returned r=-0.65 (p=0.24) with all shooters included. A strong negative correlation existed in data when P1 was included and P4 was eliminated (r=-0.94, p=0.04). A strong negative correlation was also indicated in the data when P4 was included and P1 was eliminated (r=-0.97, p=0.03). All three relationships indicated that an increase in aim point steadiness, as measured by Std10.0, was associated with a decrease in error in the Y-axis on target. This is an expected result, as discussed in relation to error in the X-axis for the pistol group, as the longer time the aim point spends inside the 10 ring, the more chance of hitting the target closer to the centre and reducing error. However, with P1 and P4 both eliminated, no relationship was evident. As such, the relationship between PosY and aim point fluctuation is unclear from this analysis. The effects of P1 and P4 in these relationships are summarised in table 5.2.3.1.8.

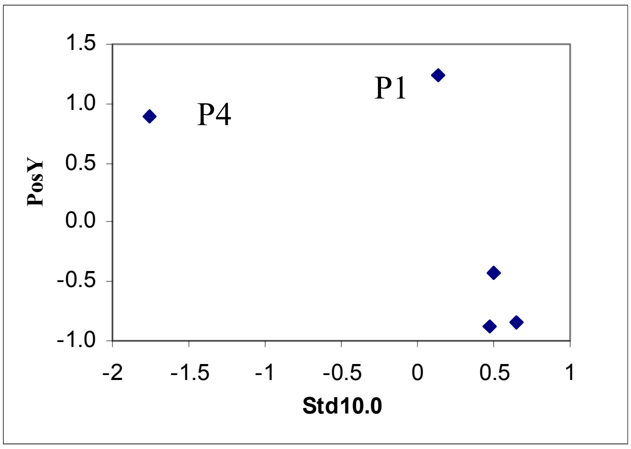


Figure 5.2.3.1.15: Scattergraph of Std10.0 and PosY (z scores) for the pistol shooting group.

Table 5.2.3.1.8: Comparison of correlations between aim point parameters and PosY for the pistol shooting group with and without P1 and P4

	PosY			
	Group	***-P4***	-P1	*-P1P4*
Std.10.0	**-0.64**	***-0.94***	-0.97	*-0.33*
Std.10a0	**-0.29**	***0.54***	-0.86	*0.47*
Length	**0.49**	***0.13***	0.85	*0.09*
LengthX	**0.40**	***0.10***	0.65	*0.09*
LengthY	**0.53**	***0.24***	0.95	*0.03*

-P4 refers to the correlation using data from only 4 shooters with P4 eliminated (N=4)
-P1 refers to the correlation using data from only 4 shooters with P1 eliminated (N=4)
-P1P4 refers to the correlation using data from only 3 shooters with P1 and P4 eliminated (N=3)

In summary, the relationship between aim point fluctuation and shooting performance for the pistol-shooting group seemed quite strong. Std10.0 and Result correlated significantly at $p<0.05$, while reasonable r values were returned between Result and Length, and Result and LengthY. Further, in more general terms, all Std parameters were correlated positively with Result and negatively with PosX and PosY, while all Length parameters were negatively correlated with Result and positively correlated with PosX and PosY, with reasonably high r values. This further supported the existence of a relationship between aim point fluctuation and shooting performance, with an increase in aim point fluctuation being associated with a decrease in performance. However, as for body sway correlations, the influence of P4 clouded the statistical analysis, with nearly all relationships weakening when P4 was eliminated. The exception was the correlation between Result and Std10.0, which showed a strong relationship with and without P4. Both P1 and P4 influenced correlations between aim point parameters and PosY, providing inconclusive data for these relationships.

This data suggests that Std10.0 is a good performance predictor of result for this group, with an increase in aim point steadiness being associated with an increase in result. While other relationships have not been discounted, more research with greater numbers of shooters is required to better define their relationship with performance.

5.2.3.1.4 Relationship between body sway and aim point parameters for the pistol shooting group

The correlation matrix between body sway and aim point data for the pistol shooting group is detailed in table 5.2.3.1.9 (N=5). As can be noted, no relationships were significant at $p<0.05$.

Table 5.2.3.1.9: Correlation Matrix: Coefficients from correlations between body sway and aim point parameters for the pistol shooting group (N=5)

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0	**0.14**	**-0.19**	**0.73**	**0.64**
Std10a0	**0.40**	**0.07**	**0.78**	**0.73**
Length	**-0.11**	**0.27**	**-0.69**	**-0.60**
LengthX	**0.02**	**0.37**	**-0.51**	**-0.43**
LengthY	**-0.20**	**0.17**	**-0.77**	**-0.68**

COPx parameters showed only weak links with aim point parameters based on low correlation coefficients reported in table 5.2.3.1.9. This indicated that sway perpendicular to the line of shot did not influence the point of aim of the gun on the target. Scattergraphs showed a group of three or four shooters clustered fairly close, with one or two shooters 'outlying'. Regardless, no clear relationship was apparent. An example of the relationship between COPx and aim point parameters is presented in figure 5.2.3.1.16.

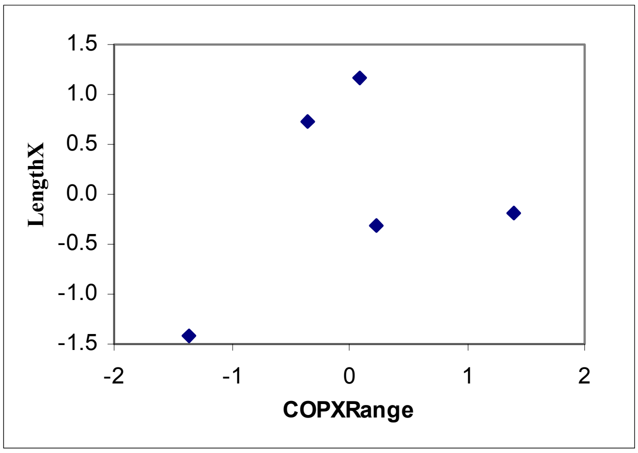


Figure 5.2.3.1.16: Scattergraph of COPxRange and LengthX (z scores) for the pistol shooting group.

The exception to this pattern was the relationship between COPx parameters and Std10.0. P1 and P4 influenced this data considerably, as can be noted in figures 5.2.3.1.17 and 5.2.3.1.18. With P1 included and P4 removed, the correlation between

COPxLength and Std10.0 strengthened from r=0.14 (p=0.82) to r=-0.85 (p=0.15) with P4 removed, while the correlation between COPxRange and Std10.0 improved from r=-0.19 (p=0.76) to r=-0.71 (p=0.29). Both indicated that an increase in body sway perpendicular to the line of shot may be associated with a decrease in aim point steadiness. This is a logical association, with an increase in sway likely to move the gun, and hence the aim point, more. Correlations for the group without P1 returned r=0.27 (p=0.73) between COPxLength and Std10.0 and r=-0.37 (p=0.61) between COPxRange and Std10.0. While these coefficients do not vary from those obtained with P1 included in analysis, indicating no relationship exists between these parameters, this shooter does give the correlation its strength when P4 is removed. As can be noted in figure 5.2.2.1.17, it is difficult to assess whether the remaining three shooters show a relationship between these parameters. This clouds the possibilities that are presented by this data.

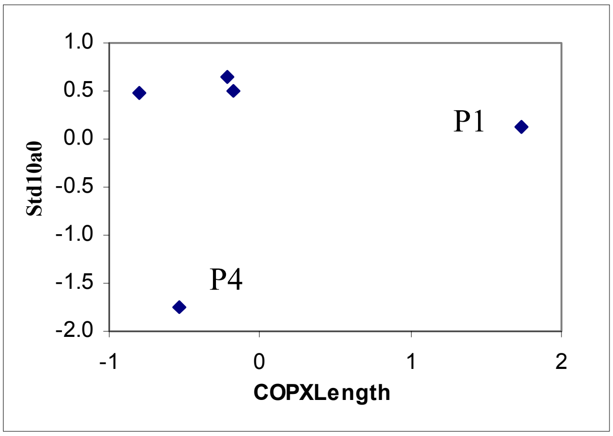


Figure 5.2.3.1.17: Scattergraph of COPxLength and Std10.0 (z scores) for the pistol shooting group.

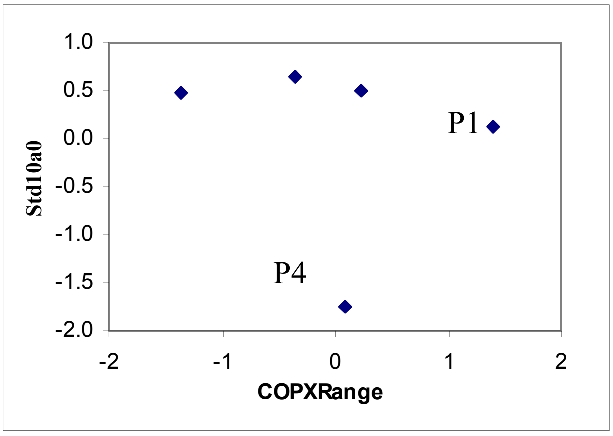


Figure 5.2.3.1.18: Scattergraph of COPxRange and Std10.0 (z scores) for the pistol shooting group.

COPy parameters returned higher coefficients than COPx parameters for correlations with aim point parameters. Coefficients of r≥0.60 were returned in eight out of ten correlations, although these relationships are significant between p=0.14 and p=0.28 only. In broad terms, this might indicate a link between aim point fluctuation and body sway, with an increase in sway, as measured by COPy parameters, being associated with an increase aim point steadiness, as measured by Std parameters, and a reduction in aim point length values. This surprising association was also evident in some rifle shooters (section 5.2.2.2). As discussed in relation to the rifle shooters, an optimal amount of body sway may exist for these pistol shooters and further reduction of sway beyond this level is detrimental to performance. However, as can be noted in figures 5.2.3.1.19 and 5.2.3.1.20, P4 has influenced these correlations, and without this shooter, no relationship was evident in these relationships. The influence of P4 to correlations between body sway and aim point parameters is summarised in table 5.2.3.1.10 at the end of this section.

Figure 5.2.3.1.19: Scattergraph of COPyLength and Std10a0 (z scores) for the pistol shooting group.

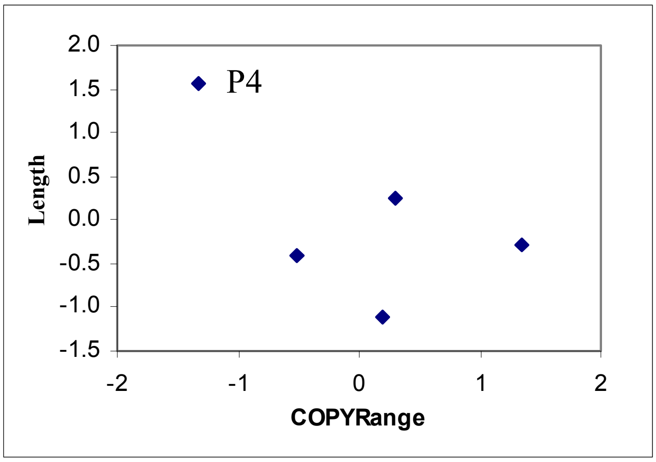


Figure 5.2.3.1.20: Scattergraph of COPyRange and Length (z scores) for the pistol shooting group.

P4 was particularly influential to the relationship between COPy parameters and Std10.0 (figures 5.2.3.1.21 and 5.2.3.1.22). The correlation between COPxLength and Std10.0 strengthened from r=0.14 (p=0.82) to r=-0.85 (p=0.15) with P4 removed, while the correlation between COPxRange and Std10.0 improved from r=-0.19 (p=0.76) to r=-0.71 (p=0.29). Without P4, the relationship indicated that as body sway perpendicular to the line of shot increased, aim point steadiness decreased. This is a logical association, with an increase in sway likely to move the gun, and hence the aim point, more. P1 is less evident in these relationships, although the correlations are strengthened with this shooter included and P4 eliminated.

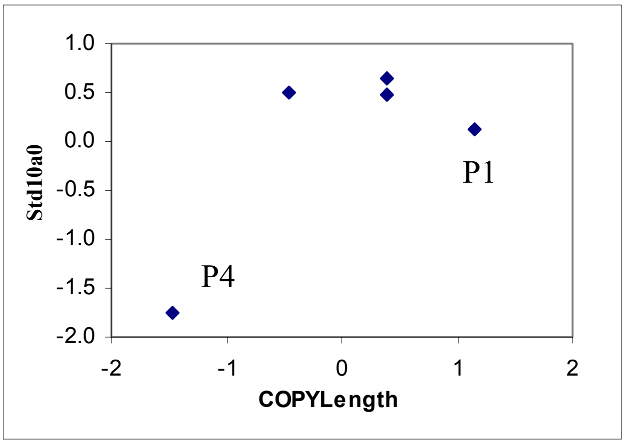


Figure 5.2.3.1.21: Scattergraph of COPyLength and Std10.0 (z scores) for the pistol shooting group.

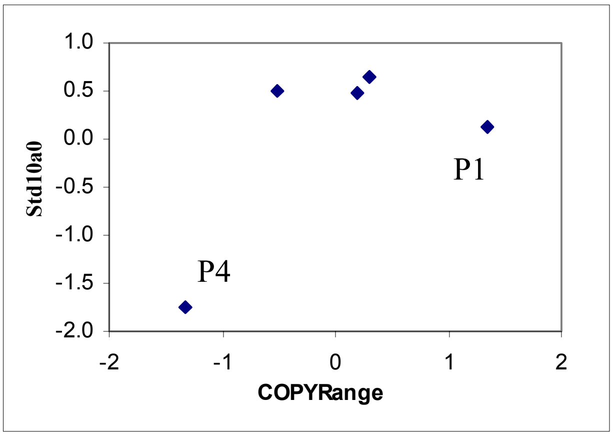


Figure 5.2.3.1.22: Scattergraph of COPyRange and Std10.0 (z scores) for the pistol shooting group.

Table 5.2.3.1.10 summarises the effect of P4 on correlations between body sway parameters and aim point parameters for the pistol-shooting group.

Table 5.2.3.1.10: Comparison of correlations between body sway and aim point parameters for the pistol shooting group with P4 (N=5) and without P4 (N=4)

	COPxLength		COPxRange		COPyLength		COPyRange	
	Group	*-P4*	Group	*-P4*	Group	*-P4*	Group	*-P4*
Std.10.0	**0.14**	***-0.85***	**-0.19**	***-0.71***	**0.73**	***-0.65***	**0.64**	***-0.74***
Std.10a0	**0.40**	***0.35***	**0.07**	***0.32***	**0.78**	***0.08***	**0.73**	***0.15***
Length	**-0.11**	***0.33***	**0.27**	***0.46***	**-0.69**	***0.09***	**-0.60**	***0.15***
LengthX	**0.02**	***0.30***	**0.37**	***0.44***	**-0.51**	***0.07***	**-0.43**	***0.12***
LengthY	**-0.20**	***0.44***	**0.17**	***0.53***	**-0.77**	***0.23***	**-0.68**	***0.28***

(* p<0.05)

-P4 refers to the correlation using data from only 4 shooters with P4 eliminated (N=4)

In summary, the relationship between body sway and aim point fluctuation was unclear from this analysis due to the small N and existence of one or two shooters 'outlying'. If the five shooters represent the normal distribution of elite pistol shooters, then an association was indicated between sway parallel to the line of shot and aim point fluctuation, although these relationships were not significant at $p<0.05$. Surprisingly, these results indicated that an increase in body sway was associated with an increase in aim point steadiness and a decrease in aim point length, as the opposite might be expected. Similar relationships were found for some rifle shooters. It may be that an optimal amount of body sway exists, and reduction of sway below this level is detrimental to performance for these pistol shooters. However, with P4, the outlying shooter, eliminated from the group, these relationships were not evident in the data. Conversely the relationship between Std10.0 and body sway parameters was strengthened. These relationships indicated that an increase in body sway may be associated with a decrease in aim point steadiness, which is a more expected and logical relationship.

The limitations that existed in the rifle shooting group analysis also exist for the pistol shooting group analysis in this study of pistol shooters. Subject numbers were small, reducing statistical power. Further, this small number did not allow for the separation of male and female shooters within this group. As mentioned in the rifle shooting group analysis, elite male and female rifle shooters have been found to be significantly different in body sway control (Era *et al.*, 1996). As such, this grouping of shooters in this study may have influenced results, although there was no hierarchical order evident between male and female shooters in any parameter (body sway, aim point and performance) in this study. The unavailability of aim point co-ordinates in the time frame of this study limited the analysis of the aim point parameters to those provided by the SCATT software. These parameters may not be sensitive to the aim point strategies reported by Zatsiorski and Aktov (1990) and Heinula (1996). As discussed previously, this will affect absolute data and, as a result, statistical analysis. Further research is required to examine the relationship between body sway, aim point and performance with larger numbers of shooters. Also, a more thorough analysis of aim point fluctuation is required when examining the relationship between aim point and performance and between aim point and body sway.

It is likely that these results have been influenced by the elite nature of the group, as discussed in the rifle group analysis (5.2.2.1). All the skills required in shooting to perform optimally, such as the control of body sway and aim point fluctuation, would be expected to be trained to a very high level, such that a slight error in any one can result in a performance decrement. These errors will not necessarily be generated in the same skill for each shooter, nor for different shots for the same shooter, as problem areas might be expected to be identified and improved from group of shots or even on a shot to shot basis. The lack of association may also be due to accommodation skills of the shooters, who make upper body adjustments to accommodate body sway at the feet.

5.2.3.2 Pistol: Individual Analysis

As for the rifle shooting analysis, the pistol shooter with the highest Result (P5) was chosen for detailed analysis. Repeating, parameters are reported for the pistol shooting analysis without the corresponding time period of measure, as only the 1s period was analysed.

5.2.3.2.1 Shooting Performance for P5

Table 5.2.3.2.1 details the mean shooting performance for P5 over 20 shots (N=20 shots).

Table 5.2.3.2.1: Shooting performance for P5 (N=20 shots)

		Mean	*SD*
Result	score (max 10.9)	**10.07**	***0.45***
PosX	horizontal distance to centre of target (mm)	**4.8**	***3.2***
PosY	vertical distance to centre of target (mm)	**4.7**	***3.0***

As mentioned, P5 returned the highest mean Result of the pistol-shooting group of 10.07. This value was well above the mean Result for the pistol shooting group of 9.73, but slightly lower than the mean Result for the rifle shooting group (10.09) and for R2 (10.44).

PosX of 4.8mm was below the pistol group mean of 6.7mm and was the smallest value returned for the group. PosY of 4.7mm was also below the pistol group mean of

5.9mm and was the second smallest of the group. Both PosX and PosY for P5 were larger than the values obtained for the rifle group (PosX=1.6mm, PosY=1.1mm) and R2 (PosX=1.0mm, PosY=0.7mm). PosX was larger than PosY for P5, indicating slightly more error of shot occurring in the X, or horizontal, axis. This was also the case for the pistol-shooting group, rifle shooting group, R2 and three of the remaining four pistol shooters (Appendix C).

5.2.3.2.2 Body sway measures and relationship with performance for P5

Table 5.2.3.2.2 shows mean values for body sway parameters for P5 (N=20 shots).

Table 5.2.3.2.2: Mean body sway data for P5 (N=20 shots)

		Mean	***SD***
COPxLength	mm	**2.79**	***0.84***
COPxRange	mm	**1.77**	***0.75***
COPyLength	mm	**2.54**	***1.01***
COPyRange	mm	**1.02**	***0.35***

COPxLength and COPxRange values of 2.79mm and 1.77mm respectively were lower than the pistol shooting group mean of 3.01mm and 1.89mm and were the second lowest in the group. However, mean COPyLength and COPyRange values of 2.54mm and 1.02mm respectively were above the pistol group mean of 2.33mm and 0.96mm and were the second largest in the group. On a general level, then, it would seem that a reduced level of body sway is not the most important factor influencing performance for the pistol group, as P5 achieved the best Result but not the most stable stance.

P5 showed larger COP lengths and COP ranges in the X-axis compared with the Y-axis. This is similar to the pistol group characteristics. However the rifle group showed greater values in COPyLength than COPxLength. This was discussed in section 5.2.2.1.

Table 5.2.3.2.3 details the results of correlation statistics between body sway parameters and shooting performance data for P5 (N=20 shots).

Table 5.2.3.2.3: Correlation Matrix: Coefficients from correlations between body sway parameters and shooting performance for P5 (N=20 shots)

	Result	PosX	PosY
COPxLength 1	**-0.06**	**0.14**	**-0.01**
COPxRange 1	**-0.01**	**0.11**	**-0.08**
COPyLength 1	**-0.28**	**0.24**	**0.21**
COPyRange 1	**-0.17**	**0.18**	**0.06**

No associations were found between body sway parameters and shooting performance for P5, significant at $p<0.05$. As can be noted from table 5.2.3.2.3, coefficients did not exceed $r=0.28$ ($p<0.25$), which would indicate that the relationship between body sway and Result for P5 is reasonably weak. As such, other skill variables must be more influential to performance. Similarly, coefficients for correlations between body sway parameters and PosX and PosY were all less than $r=0.25$ ($p<0.31$), indicating only a very weak association exists between these variables.

While body sway seemed unrelated to performance for P5, analyses of other pistol shooters showed different results for different individuals (Appendix F). P1 returned strong correlations between COPxLength and Result ($r=-0.52$, $p=0.02$), COPxLength and PosX (r=0.52, p=0.02) and COPxRange and PosX (r=0.49, p=0.03) that were all significant at p<0.05. All relationships indicated that an increase in body sway was associated with a decrease in the score on target and an increase in error of shot, as might be expected. Similar relationships were found for rifle shooters. Repeating, on a general level, an increase in body sway may indicate a lower level of skill for that shooter, which might be expected to be associated with a poorer performance. More specifically, an increase in body sway will generate increased gun movement, which in turn may generate greater aim point fluctuation and reduced scores. Two other shooters showed similar associations between body sway parameters and Result (P2, COPxLength, r=-0.35, p=0.13; P4, COPyRange, r=-0.34, p=0.15), although these were not strong, and were significant only at p≤0.15. The remaining shooter, P3, like P5, showed no association between body sway and Result. However, P3 did return a negative correlation between with COPyLength and PosX (r=-0.44, p=0.05) indicating that an increase in sway parallel to the line of shot was associated with a decrease in error of shot in the horizontal axis on target. This unusual relationship (both the negative correlation and Y-X association was unexpected) was also evident in some rifle shooters and discussed in that section (5.2.2.2). These results suggest that the influence of body sway on performance is quite different for different individuals, with the degree of association and the sway direction most influential to performance different for different shooters. However, in contrast to some rifle shooters, no pistol shooter returned a relationship that indicated an increase in body sway was associated with an increase in performance.

Multiple R values for regressions between body sway parameters and performance were quite low for P5 (table 5.2.3.2.4). COPyLength and COPyRange (R=0.35, p=0.34) combined to predict only 12.1% of the variance in Result. While this combination is a better predictor than single body sway parameters, it still indicates the link between body sway and performance is weak for P5. Body sway was a poor predictor for PosX and PosY also. Overall, then, the influence of body sway on performance seems to be small for P5, with no strong associations evident from correlation or multiple regression analysis.

Table 5.2.3.2.4: Results of regression analysis between body sway parameters and performance for P5

	Var (v)	R	R^2 (%)	P	Cv	Regression Equation
Result	**2**	**0.35**	**12.1**	**0.34**	**1.1**	10.2 - 0.336 COPyLength + 0.676 COPyRange
PosX	**2**	**0.26**	**6.8**	**0.55**	**1.1**	3.46 + 1.52 COPyLength - 2.46 COPyRange
PosY	**2**	**0.39**	**15.6**	**0.24**	**1.3**	4.67 + 2.90 COPyLength - 7.24 COPyRange

Of the remaining four shooters, only one returned a regression that was significant at p<0.05 (Appendix F), indicating that body sway was not strongly associated with performance for most shooters. COPxLength, COPxRange and COPyRange combined to predict 45.8% of the variance in Result for P1 (R=0.68, p=0.02). Interestingly, body sway in both x and y axes seemed to influence performance, with both present in the best regression equation (table 5.2.3.2.4). Further, both range and length measures were present, indicating an independent contribution by these parameters and suggesting that the information provided by using both range and length measures to quantify COP is useful. Of the correlations discussed previously for P2, P3 and P4, only one body sway parameter was present in the best regression equation. As such, no more information was provided from this analysis to that already mentioned in the correlation analysis discussion.

Overall, it would seem that body sway did not influence performance strongly for P5. However, one shooter showed strong associations between body sway and performance, indicating an increase in body sway was associated with a decrease in score and an increase in errors of shot. Also, one shooter returned a correlation between body sway and error of shot that was significant at p=0.05. Interestingly, this relationship indicated an increase in body sway was associated with a decrease in error of shot. Further, it suggested a Y-X association between body sway and shot on target existed. Both associations were unexpected, but were evident in rifle shooters, as discussed in section 5.2.2.2. The remaining two shooters showed some association between body sway and Result, although this was significant only at p≤0.15. It would seem, then, body sway is related to performance in pistol shooting for some shooters, with this relationship being different in terms of degree and direction of association for different shooters.

5.2.3.2.3 Aim point measures and relationship with performance for P5

Table 5.2.3.2.5 reports mean values for aim point parameters for P5 (N=20 shots).

Table 5.2.3.2.5: Mean aim point data for P5 (N=20 shots)

		Mean	*SD*
Std10.0	% time	**49.3**	***14.9***

Std10a0	% time	**63.4**	***17.6***
Length	mm	**119.9**	***19.4***
LengthX	mm	**84.1**	***16.3***
LengthY	mm	**68.4**	***12.2***

The mean Std10.0 value for P5 was 49.3%, which was well above the pistol group average of 42.1% and was the largest in the group. Mean Std10a0 (63.4%), conversely, was below the pistol group average of 65.2% and was 4th largest in the group. P5 returned mean Length and LengthX values of 119.9mm and 84.1mm respectively, which were above the group average of 114.9mm and 76.1mm respectively. The LengthY value of 68.4mm was slightly below the pistol group average of 70.7mm. However, all values were the second largest in the group. This indicates that P5 possessed one of the most fluctuating aim points of the group. Generally, then, this might suggest that an increase in aim point fluctuation does not influence performance in pistol shooting, as P5 achieved the best score but generated one of the largest aim point lengths.

Interestingly, P5 showed the most stable aim point in terms of centring on the target centre (as measured by Std10.0), but returned above group average aim point lengths and below group average Std10a0 values. This indicated that, relative to the group, P5 seemed to show poor aim point stability, but was more accurate with the aim point position. So while the aim point described a large trace, the trace centred largely on the target centre. For P5, this translated into the best mean result of the group.

Table 5.2.3.2.6 details the results of correlation statistics between aim point parameters and shooting performance data (N=20 shots).

Table 5.2.3.2.6: Correlation Matrix: Coefficients from correlations between aim point parameters and shot performance for P5 (N=20 shots)

	Result	PosX	PosY
Std10.0	**0.13**	**-0.12**	**-0.09**
Std10a0	**0.09**	**-0.16**	**-0.02**
Length	**-0.46***	**0.58****	**0.16**
LengthX	**-0.34**	**0.47***	**0.08**
LengthY	**-0.51***	**0.58****	**0.23**

(*p<0.05,p<0.01)**

P5 showed no link between Std10.0 and shooting performance, as measured by Result, PosX and PosY. This indicated that aim accuracy, as indicated by Std10.0, did not influence performance for P5. This is perhaps surprising, given that P5 showed the best Std10.0 value of the pistol group and the best Result, while other aim point parameters returned by P5 were poor relative to the group. Further, the group based statistical analysis showed a strong association between Std10.0 and Result. P5 also showed no association between Std10a0 and performance, indicating that the quality of hold, as measured by Std10a0, did not influence performance for P5.

Conversely, Std10.0 and Std10a0 were related to performance for three of the remaining four pistol shooters, as summarised in table 5.2.3.2.7. All relationships indicated that an increase in aim point steadiness in the target centre, as measured by Std10.0, and an increase in general aim point steadiness, as measured by Std10a0, were related to an increase in score and a decrease in errors of shot. These associations are logical and were evident in some rifle shooters (section 5.2.2.2). On a general level, an increase in aim point steadiness might be indicative of greater skill, which would be expected to be associated with better performance. Specifically, the greater amount of time the aim point spends inside the 10 ring, the greater the chance of scoring 10 or above, and increasing the chance achieving a higher score and reducing errors compared to an aim point which spends more time outside this area. These results suggest that aim point control is important to performance for some, but not all, pistol shooters at the elite level, and the level of this importance is different for different shooters.

Table 5.2.3.2.7: Summary of correlations between Std measures and performance for individual pistol shooters (P5 excluded)

Parameters		Shooter	r	p
Std10.0	Result	P1	**0.47**	**0.04**
		P2	**0.39**	**0.08**
		P3	**0.63**	**<0.01**
	PosX	P3	**-0.40**	**0.08**
	PosY	P1	**-0.51**	**0.02**
		P3	**-0.36**	**0.12**
Std10a0	Result	P1	**0.49**	**0.03**
	PosX	P1	**-0.46**	**0.04**
	PosY	P4	**-0.30**	**0.20**

In contrast to the relationship between Std measures and performance, P5 returned numerous correlations between aim point length measures and performance, significant at $p<0.05$. Result was linked with Length ($r=-0.46$, $p=0.04$) and LengthY ($r=-0.51$, $p=0.02$). Figures 5.2.3.2.1 and 5.2.3.2.2 show the scattergraphs of these relationships. Both indicated that as aim point length increased, performance decreased for P5. This is a logical relationship, as discussed in the rifle analysis (section 5.2.2.3) where this relationship was also found. Repeating, in general terms, an increase in aim point length indicates less aim point control, which might be expected to be associated with a decrease in performance. More specifically, an increase in aim point length is likely to be associated with a decrease in the time spent on the target centre and may move the aim point across lower scoring rings than a shorter aim point length, although this cannot be discerned without range data. This decreases the chance of the point of shot coinciding with the instant at which the aim point is located on the target centre and increases the chance of shooting when on lower score rings. Hence the likelihood of lower scores increased. A similar relationship was indicated in one other shooter (P1) between Result and Length (r=-0.47, p=0.04) and between Result and LengthY (r=-0.39, p=0.09).

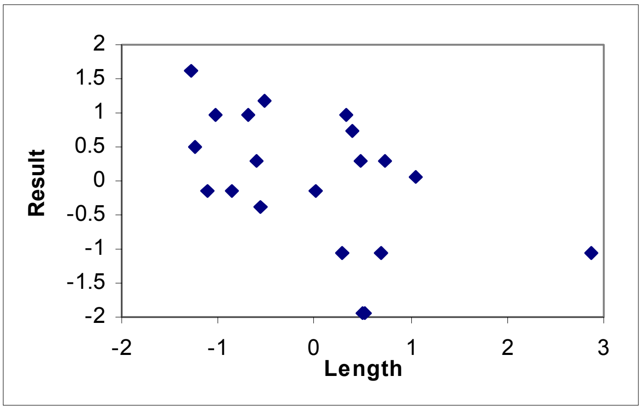


Figure 5.2.3.2.1: Scattergraph of Length and Result (z score) for P5.

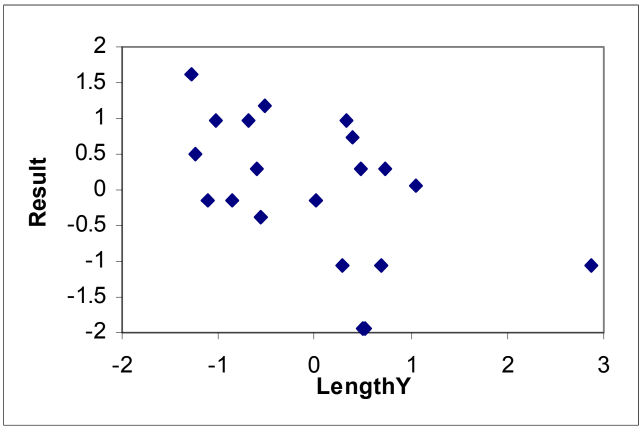


Figure 5.2.3.2.2: Scattergraph of LengthY and Result (z score) for P5.

The stronger relationship returned by P5 between Result and LengthY (r=-0.51) compared with Result and LengthX (r=-0.34) indicated that aim point fluctuation in the Y-axis influenced Result more strongly than fluctuation in the X-axis for P5. This was also the case for P1 (Result – LengthY, r=-0.39, Result – LengthX, r=-0.33). The remaining shooters showed only very weak relationships between aim point lengths and Result (Appendix F).

All correlations between aim point lengths and PosX, as represented by figures 5.2.3.2.3, 5.2.3.2.4 and 5.2.3.2.5, were significant at p≤0.05 for P5. PosX and Length s1 (r=0.58, p=0.01), PosX and LengthX s1 (r=0.47, p=0.04) and PosX and LengthY s1 (r=0.58, p=0.01) all indicated that as aim point length increased, the error of shot in the X-axis increased. This is an expected result, as discussed in the rifle group and individual analysis sections (5.2.2.1 and 5.2.2.2) where this relationship was also evident.

Figure 5.2.3.2.3: Scattergraph of LengthX and PosX (z score) for P5.

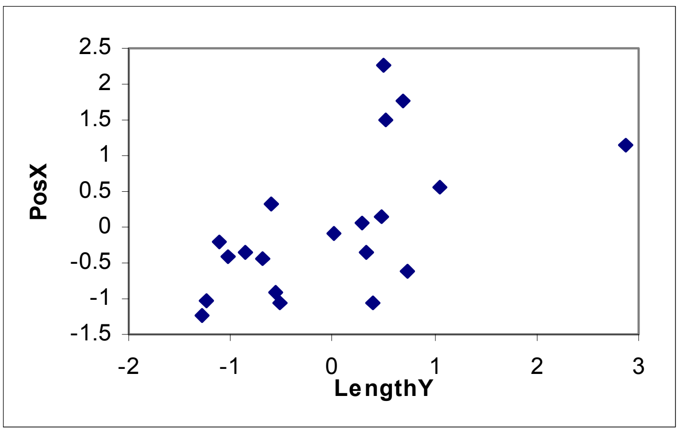


Figure 5.2.3.2.4: Scattergraph of LengthY and PosX (z score) for P5.

Figure 5.2.3.2.5: Scattergraph of Length and PosX (z score) for P5.

Interestingly, both an X-X and an Y-X association were evident in this data for P5. As discussed, while the X-X association is expected and logical, the Y-X association is not. Recalling from section 5.2.2.2, numerous Y-X and X-Y associations between aim point fluctuation and PosX existed for rifle shooters also. This suggests that as the aim point length in the vertical axis increases, errors in the horizontal axis also increase. This relationship was not strongly evident in other pistol shooters, with only P1 ($r=-0.34$, $p=0.15$) showing an association between PosX and LengthY significant at $p<0.20$. It may be that a technical aspect of P5 in stabilising the aim point in the vertical direction affects the point of aim in the horizontal direction at the point of shot. It may also be that some feedback on the horizontal position of the aim point relative to the target centre is provided by vertical aim point fluctuation. However, it could reflect a more general relationship between aim point fluctuation and error. The fact that all length measures are related to PosX supports this suggestion.

Results from regressions between body sway parameters and performance chosen from evaluation of the Cv plot are presented in table 5.2.3.2.8.

Table 5.2.3.2.8: Results of regression analysis between aim point parameters and performance for P5

	Var (v)	R	R^2 (%)	p	Cv	Regression Equation
Result	**1**	**0.51**	**25.7**	**0.05**	**0.0**	11.3 - 0.0185 LengthY
PosX	**1**	**0.58**	**34.1**	**0.01**	**0.6**	- 5.47 + 0.151 LengthY
PosY	**1**	**0.23**	**5.4**	**0.33**	**-0.7**	0.80 + 0.0565 LengthY

As can be noted from table 5.2.3.2.8, regression equations added no information to that gained from correlation analysis previously discussed. LengthY, which correlated at $p<0.05$ with Result and PosX, was the only parameter to feature in the regression equations when all aim point parameters were treated together. This indicates that aim point fluctuation in the vertical axis, as measured by LengthY, is the major aim point influence on performance for P5.

Other shooters returned different aim point parameters in best regressions between aim point parameters and performance. Table 5.2.3.2.9 summarises the regressions returned by the remaining shooters that were significant at $p\leq0.10$. As can be noted, a combination of measures contributed to the best regression for most of these analyses. Also of interest is the presence of Std10.0 in regressions for all three shooters. This is not surprising as the group-based analysis indicated a strong link between Std10.0 and performance, although P5 showed no association between these parameters. The remaining shooter, P4, shoed no association between aim point parameters and performance significant at $p<0.20$. This provides another example of the individuality of results for this analysis.

Table 5.2.3.2.9: Best regressions between aim point parameters for individual pistol shooters significant at p≤0.10 (P5 excluded)

	Shooter	Parameters included in regression	R	R^2	p
Result	**P1**	Std10.0, LengthX	**0.55**	**29.9**	**0.05**
	P3	Std10.0, Std10a0	**0.73**	**53.0**	**<0.01**
PosX	**P1**	Std10a0	**0.46**	**21.1**	**0.04**
	P3	Std10.0, LengthX, LengthY	**0.60**	**35.6**	**0.06**
PosY	**P2**	Std10.0, LengthX	**0.49**	**24.1**	**0.10**
	P3	Std10.0, Std10a0, LengthX, LengthY	**0.69**	**47.8**	**0.04**

In summary, aim point lengths were related to performance for P5, with a reduced aim point fluctuation, as measured by aim point length, associated with an increase in performance and a decrease in error of shot in the horizontal axis on the target. Interestingly, no relationship was evident between Std10.0 and Result for P5, despite P5 returning the best Std10.0 value and best Result of the group. Further, Std10.0 was the only aim point parameter in which P5 was the best (1st) in the group, while all other aim point parameters were 4th of the 5 shooters in this study. It would seem that P5 has the ability to centre the aim point on the target during aiming, even though the aim point is fluctuating considerably, as indicated by the large aim point length values. It may also represent an aim point strategy of P5, which differs from the other shooters, although it was not possible to assess this due to the unavailability of aim point co-ordinates. Regardless, this translates into the best Result of the group for P5. Other shooters also showed relationships between aim point fluctuation and performance. In all cases, an increase in aim point fluctuation, as indicated by a decrease in Std measures or an increase in aim point lengths, was associated with a decrease in performance. Recalling from the group analysis, Std10.0 was strongly related to performance, while aim point lengths showed some association. This suggests that aim point fluctuation is important to performance in pistol shooting at the elite level. Further, while the direction of this relationship was always the same, with an increase in aim point fluctuation associated with a decrease in performance, the degree of association and important aim point parameters were different for different shooters.

5.2.3.2.4 Relationship between body sway and aim point parameters for P5

Table 5.2.3.2.10 details the results of correlation statistics between body sway data and aim point data (N=20 shots).

Table 5.2.3.2.10: Correlation Matrix: Coefficients from correlations between body sway and aim point parameters for P5 (N=20 shots)

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0	**-0.23**	**-0.22**	**-0.34**	**-0.17**
Std10a0	**-0.16**	**0.03**	**-0.59****	**-0.40**
Length	**0.06**	**-0.09**	**0.04**	**0.01**
LengthX	**0.09**	**-0.11**	**0.09**	**0.04**
LengthY	**0.05**	**0.00**	**-0.11**	**-0.10**

(**p<0.01)

Std10.0 was not strongly related to body sway parameters for P5, with the correlation between Std10.0 and LengthY ($r=-0.34$, $p=0.15$) returning the largest r value. This relationship indicated that an increase in body sway, as measured by COPyLength, may be associated with a decrease in aim point steadiness. This is a logical link, and similar to that found in some rifle shooters, as discussed in section 5.2.2.2. Repeating, an increase in body sway might be expected to produce more gun, and hence aim point, movement, reducing the amount of time the aim point spends inside a certain area on target. Two other shooters also showed an increase in sway was associated with a decrease in Std10.0, with both P1 (Std10.0 - COPxLength, r=-0.47, p=0.04 and COPxRange, r=-0.51, p=0.02) and P3 (COPxRange, r=-0.44, p=0.05) returning relationships significant at $p \leq 0.05$. This suggested body sway and aim point fluctuation are related for some but not all shooters, with an increase in body sway being associated with a decrease in aim point steadiness.

Std10a0 was strongly correlated with body sway for P5, with Std10a0 and COPyLength (r=-0.59, p=0.01), while Std10a0 was also associated with COPyRange (r=-0.40, p=0.08). These relationships are represented in figures 5.2.3.2.6 and 5.2.3.2.7. Both indicate that an increase in sway parallel to the line of was associated with a decrease in aim point steadiness. This is a logical relationship, as discussed in the rifle group and individual analyses (section 5.2.2.1 and 5.2.2.2). Repeating, an increase in sway might be expected to increase gun movement, decreasing the steadiness of the aim point. A similar association was evident in two other shooters (P1, COPxLength, r=-0.56, p=0.01, COPxRange, r=-0.43, p=0.06; P3, COPxLength, r=-0.62, p<0.01, COPxRange, r=-0.52, p=0.02). Similar to the conclusions for the relationship between body sway and Std10.0, these results suggests that body sway and aim point fluctuation, as measured by Std10a0, are associated for some but not all shooters. As expected, stronger correlations were returned between Std10a0 and body sway compared with Std10.0 and body sway. This was also found in the rifle shooting individual analyses. As discussed, Std10a0 represents a better measure for direct comparison of body sway and aim point fluctuation.

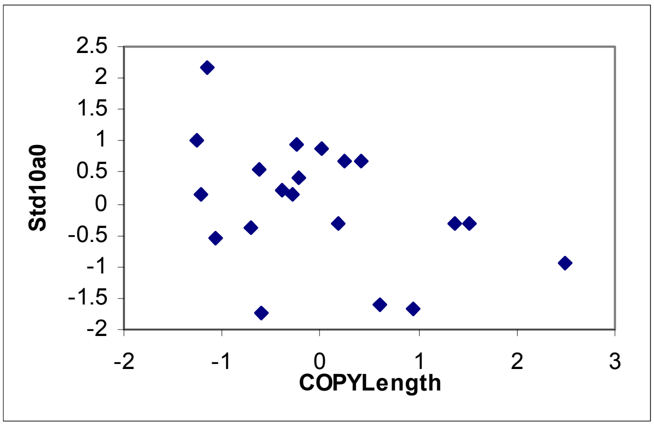


Figure 5.2.3.2.6: Scattergraph of COPyLength and Std10a0 (z score) for P5.

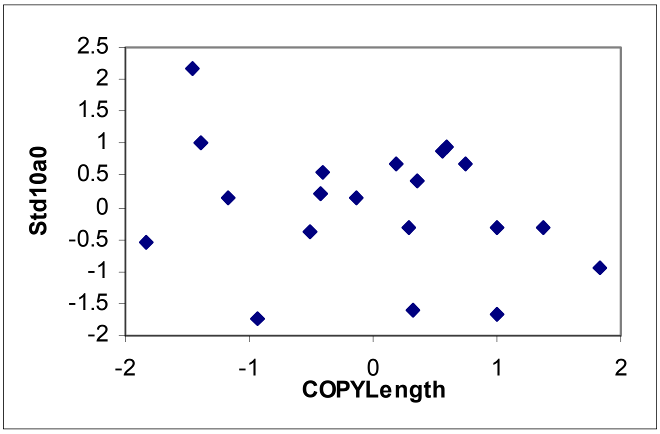


Figure 5.2.3.2.7: Scattergraph of COPyRange and Std10a0 (z score) for P5.

Interestingly for P5, while body sway parameters were related to Std10a0, neither were related to performance, as measured by Result, PosX and PosY. Further, As such, the relationship between body sway and Std10a0 may not be important to P5. It is unclear if and how this set of relationships may interact without closer examination of aim point co-ordinates.

Although aim point lengths and body sway seemed unrelated for P5, all other shooters returned a least one correlation between these parameters that was significant at

$p<0.10$. Table 5.2.3.2.11 reports the strongest correlation for each of the remaining four shooters. This suggests that the lack of association between body sway and aim point lengths is specific to P5. This may have occurred due to P5 accommodating the sway produced at the feet by adjusting the upper body and gun. As such, the aim point may have been maintained within a small area on the target, while other factors generated a higher frequency, low amplitude movement within this area, generating the relatively large aim point lengths. Muscle tremor would be a logical generator of this movement, with low movement amplitude and a frequency of approximately 5Hz-10Hz (Thomas and Whitney, 1959). However, this aim point movement cannot be substantiated without aim point co-ordinates.

Table 5.2.3.2.11: Strongest correlations between body sway parameters and aim point lengths for P1, P2, P3 and P4

	parameters correlated	**r**	**p**
P1	**COPxLength - Length**	0.43	0.06
P2	**COPyRange - LengthX**	-0.39	0.09
P3	**COPxLength - Length**	0.60	0.01
P4	**COPyRange - LengthY**	-0.53	0.02

Interestingly, results reported in table 5.2.3.2.11 show two positive and two negative correlations between body sway and aim point lengths. The positive correlation returned for P1 and P3 indicates that an increase in body sway is associated with an increase in aim point length as might be expected. The negative correlation, as returned by P2 and P4 is not expected. This indicates that an increase in body sway is associated with a decrease in aim point length. Similar associations were found in rifle shooters (section 5.2.2.2). The causes of this relationship are unclear. It may be that these shooters have an optimal level of body sway, and further reduction of this sway is detrimental to the gun hold and hence the aim point. It may be that these shooters gain better aim point feedback when swaying slightly more or some amount of sway provides a degree of dynamic stability, although with sway of less than 2mm, this would seem unlikely. It may also be aim point strategies influencing this result. More research with upper body and gun movement quantified, as well as more thorough analysis of aim point strategies would be required to better define the cause of this relationship for P2 and P4.

Results from regressions between body sway and aim point parameters chosen from evaluation of the Cv plots are presented in table 5.2.3.2.12.

Table 5.2.3.2.12: Results of regression analysis between body sway and aim point parameters for P5

	Var	R	R^2	p	Cv	Regression Equation
Std10.0	**2**	**0.49**	**24.2**	**0.10**	**1.9**	53.9 - 17.1 COPyLength + 38.2 COPyRange
Std10a0	**2**	**0.69**	**48.2**	**<0.01**	**1.9**	79.2 - 25.0 COPyLength + 46.8 COPyRange
LengthX	**2**	**0.37**	**13.7**	**0.29**	**1**	74.3 + 12.9 COPxLength - 14.7 COPxRange
LengthY	**1**	**0.11**	**1.2**	**0.65**	**-0.7**	0.80 + 0.0565 COPyLength

Multiple regression analysis showed a strong link between body sway parallel to the line of shot and aim point steadiness, as measured by Std10a0, for P5, as COPyLength and COPyRange ($R=0.69$, $p<0.01$) combined to account for 48.2% of the variance in Std10a0. This suggests that sway in the Y-axis is of particular importance to Std10a0 for P5. It also further confirms the usefulness of using COP range and length measures to assess body sway, as the combination of the two parameters accounted for 48.2% of the variance of Std10a0, compared with only 34.8% for the strongest correlation (COPyLength). Similar conclusions can be drawn from the regression analysis of Std10.0, with the same combination of body sway parameters accounting for 24.2% of the variance in Std10.0 ($p=0.10$).

Other shooters also showed stronger associations between body sway parameters and Std measures significant at $p \leq 0.02$ from multiple regression analysis. All four body sway parameters were included in the best regression for Std10a0 for P1 ($R=0.63$, $p=0.04$), for P3 ($R=0.66$, $p=0.01$) and for P4 ($R=0.78$, $p<0.01$). Interestingly for all three shooters, only one body sway parameter was included in the regression predicting Std10.0 from body sway parameters, with variance accounted for reduced from that of Std10a0 (P1, $R=0.51$, $p=0.02$; P3, $R=0.44$, $p=0.05$; P4, $R=0.40$, $p=0.23$). This suggests that body sway does not influence the Std10.0 measure as strongly as Std10a0 for these shooters. As discussed, the systematic aiming error that can influence Std10.0 may have influenced this result.

Multiple regression analysis indicated that body sway was unrelated to aim point lengths for P5, with no combination of variables showing a strong R value (table 5.2.3.2.12). This further indicates that factors independent of body sway influence aim point lengths, as found in the correlation analysis. One other shooter (P1) also showed no relationship between body sway and aim point lengths from multiple regression analysis, although, as reported in table 5.2.3.2.11, P1 did show an association between COPxLength and Length significant at $p=0.06$ (recalling: Length was eliminated prior to multiple regression analysis). The remaining three shooters showed strong associations between body sway and aim point lengths (P2, LengthY, $R=0.53$, $p=0.06$; P3, LengthX, $R=0.59$, $p=0.03$; P4, LengthX, $R=0.67$, $p=0.02$). These results further support the use of individual analysis in research with elite shooters. Interestingly, no shooter showed strong associations between body sway parameters and both LengthX and LengthY. This suggests that body sway may influence aim point fluctuation in one axis only (either X or Y) for these shooters, rather than generally (both x and y).

In summary, body sway is linked to aim point fluctuation for P5. More specifically, an increase in body sway parallel to the line of shot, as measured by COPyLength and COPyRange, was associated with a decrease in aim point steadiness, as measured by Std10a0. Interestingly, neither body sway parameters nor Std10a0 were related to performance, suggesting that this relationship may not be important to P5. Aim point lengths would also seem to be generated by factors independent of body sway.

Analyses of other shooters showed strong associations between body sway and aim point fluctuation. Two shooters showed associations between Std measures and body sway while two shooters showed associations between aim point length measures and body sway. In all cases, correlations indicated that an increase in body sway was associated with a decrease in aim point steadiness and an increase in aim point length, as expected. This indicated that body sway and aim point fluctuation are related for elite pistol shooters. This relationship is different for different shooters, with the important body sway axis and measure and the degree of association different for different shooters.

Overall, links existed for P5 between body sway and aim point parameters and also between aim point parameters and performance, but not between body sway and performance. P5 returned the best Result in the group as well as the best Std10.0 value in the group. However, no association between these variables was found in statistical analyses. Aim point lengths were strongly associated with performance for

P5, indicating that these variables are most discerning as performance predictors for this individual. Body sway did not show any association with result, although, as discussed previously, the influence of body sway, while small, may still be of practical importance to performance for P5. P5 showed a link between body sway in the Y-axis and steadiness of aim point on target, indicating that an increase in sway parallel to the line of shot was associated with a decrease in aim point stability, as measured by Std10a0. Std10a0 is a strong indicator of the steadiness of hold, as it is independent of systematic aiming errors that may be produced by the shooter. As such, it will be a good indicator also of any relationship between body sway and aim point stability. However, this factor was not related to performance, indicating that this relationship may not be important for P5.

Two points have been highlighted in this analysis. First, an individual (intra-shooter) analysis component is required in research with elite level shooters. Further, this analysis will be enhanced by a shot to shot analysis, rather than the examination of a number of shots for different individuals. Second, the use of both range and length measures provide a more thorough description of the COP trace. Further, both were included together in numerous regressions predicting aim point fluctuation and performance, indicating that both range and length measures make an independent contribution.

CHAPTER 6 CONCLUSIONS

6.1 STAGE 1

12-bit ADC is not suitable for use in force plate assessment of body sway for elite shooters due to the potential error due to quantisation and resolution provided. Using 12-bit ADC:

- Error due to quantisation represents a large percentage of body sway values in shooting for COP and horizontal force (Fx, Fy) single measures, range measures and COP length measures.

  For example, the error due to quantisation in COPx range (±0.344mm) is 10-19% of the mean group ranges found in this study (1.81-3.28mm) while COPy range (±0.372mm) is 30-50% of the mean group s (0.74-1.23mm).

- Resolution will provide only a few steps across which body sway will be measured.

  For example, the COP of a shooter weighing 750N will be measured in steps of 0.321mm in COPx and 0.455 in COPy. This would allow for only 2-9 steps across which COP ranges would be measured.

- Standard deviation and average measures will, by way of calculation, cancel much of the error due to quantisation. However, measured over only a few steps (for example, 2-9 in the expected displacement ranges), these measures will not be suitable for body sway measurement, particularly in the small measurement periods important in shooting.

16-bit ADC is required at a minimum for force plate assessment of body sway during shooting. Using 16-bit ADC:

- The error due to quantisation is considerably smaller than body sway values in shooting in single measures, range measures and length measures.

  For example, the error due to quantisation in COPx range (±0.022mm) is 0.7-1.2% of mean COPx ranges found in this study (1.81-3.28mm) while error in COPy range (±0.023mm) is 0.9-3.1% of mean COPy ranges (0.74-1.23mm).

- Resolution will provide a large number of steps across which body sway will be measured.

  For example, the COP of a shooter weighing 750N will be measured in steps of 0.023mm in COPx and 0.029mm in COPy. This would allow for 26-154 steps across which group COP ranges would be measured.

- Standard deviation and average measures will also be suitable, with the steps provided for measurement reasonable (eg. 26-154 steps in the expected COP displacement ranges mentioned above).

- Single measures of COP speed or COP velocity are not suitable for body sway assessment during shooting using 16-bit ADC.

  A single measure of absolute (resultant) COP velocity (from data sampled at 128Hz using 16-bit ADC) will be measured with error due to quantisation of ±2.864mm/s and in steps of 2.222mm/s. These values are of similar magnitude to group means in this study of 2.91-4.25mm/s at the point of shot.

- Average and standard deviation measures will contain only a very small amount of quantisation error in speed or velocity measures using 16-bit ADC. However, these parameters are still measured in steps of similar magnitude to the values expected (3.13-4.22mm/s in this study). As such, the appropriateness of these measures must be closely assessed with this point in mind by the researcher before use.

In general terms, the error due to quantisation in COP calculations:

- decreases as Fz increases. For COPx and COPy respectively, error for a 600N shooter will be ±0.014mm and ±0.019mm, compared to ±0.008mm and ±0.011mm for a 1000N shooter using 16-bit ADC.
- decreases as Mx and My decrease. Moments recorded in this study ranged from 0Nm to approximately 100Nm. Across this range, quantisation error will increase by approximately 0.008mm using 16-bit ADC which is minimal in COP measurement of shooters.
- decreases as Fx and Fy decrease, although Fx and Fy values will contribute less than ±0.001mm to error across a range of 100N. With values recorded in this study for Fx and Fy being less than 4N, the error propagated in COP calculations due to Fx and Fy will be negligible.

COP resolution increases as Fz increases, with measurement steps becoming smaller. For COPx and COPy respectively, measurement steps for a shooter weighing 600N of 0.400mm and 0.567mm compare with 0.025mm and 0.035mm for a 1000N shooter using 16-bit ADC.

6.2 STAGE 2

6.2.1 Reduction of Postural Sway Parameters

From 16 time-based body sway parameters, including range, length and speed measures in the X-axis, Y-axis and absolute (resultant) values, four body sway factors were identified. These were:

- Amplitude of body sway in the X-axis
- Speed or rate of body sway movement in the X-axis
- Amplitude of body sway in the Y-axis
- Speed or rate of body sway movement in the Y-axis

Figure 6.2.1 presents the four groupings found by PCA with the body sway parameter chosen for further analysis in this study.

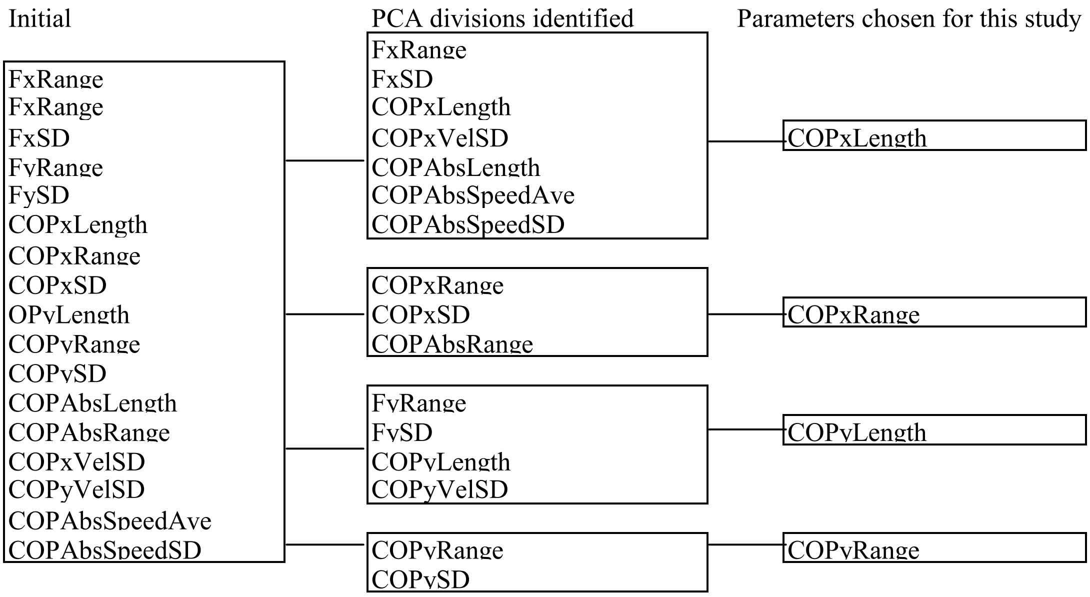


Figure 6.2.1: Four groupings of body sway parameters found by PCA and the parameters chosen to represent those factors in this study.

Range and length measures in the X and Y axes were chosen to represent each of these factors, as noted in figure 6.2.1. These measures were chosen based on appropriateness for this study and not because one was necessarily better than others.

6.2.2 Rifle and Pistol Shooting

As many factors were similar between rifle and pistol groups, conclusions have been combined.

6.2.2.1 Body sway and performance

Body sway and performance was related in pistol and rifle shooting for some but not all shooters. These relationships were specific to each individual. For example, relationships significant at $p<0.10$ varied in:

- Direction: an increase in body sway was associated with a decrease in performance for four shooters and an increase in performance for five shooters
- Time period of importance (rifle shooters only): eg. R2 showed a strong association between performance and body sway perpendicular to the line of shot in the 5s period, and between performance and body sway parallel to the line of shot in the 1s period
- Parameters associated: performance was associated with COPx parameters for four shooters and with COPy parameters for three shooters at $p<0.10$

The finding that an increase in body sway was associated with a decrease in performance is logical, as the more stable the body, the less movement of the body/gun system, which would increase the chance of good performance.

The association between an increase in body sway with an increase in performance is surprising. It may be that an optimal level of sway exists for some shooters, and further reduction of this sway is detrimental to performance.

Only two shooters (1 rifle, 1 pistol) showed an association between body sway in the X-axis sway and error of shot in the X-axis on target, or between body sway in the Y-axis and error of shot in the Y-axis on target, while seven shooters (6 rifle and 1 pistol) showed X-Y or Y-X associations. It is unclear what has caused these relationships but upper body and gun adjustment must be present for this to occur.

The relationship between body sway and performance in rifle and pistol shooting evaluated on a group basis was unclear. This is not surprising given the small amount of variability within the elite group, although within this small variability, different shooters returned different relationships between body sway, aim point fluctuation and performance. This further reduced the likelihood of finding statistical significance in the group and reflects the nature of research with elite sport.

More research with a greater number of shooters may better define the relationship between body sway and performance. However, any research of this nature requires an individual shooter component to maximise the information extracted from the data. Further, more work is required to better define the X-Y and Y-X associations evident in most shooters in this study, with the inclusion of kinematic techniques, as well as kinetic assessment of sway, to more thoroughly quantify body and gun movement.

6.2.2.2 Aim point fluctuation and performance

Aim point fluctuation and shooting performance was related for most pistol and rifle shooters. Five rifle and four pistol shooters showed associations significant at $p<0.10$. Eight of these shooters showed an increase in aim point fluctuation, as indicated by increased aim point lengths and decreased aim point steadiness, was associated with a decrease in performance.

The relationship between aim point fluctuation and performance was different for different shooters. Shooters showed different degrees and direction of association, different parameter associations and, in the case of the rifle shooters, different times of importance for relationships.

Aiming accuracy, as measured by the time spent by the aim point inside the 10 ring, in the last second before shot was a very strong indicator of performance for the pistol-shooting group, with an increase in accuracy associated with an increase in performance, as might be expected. This was also found to be strongly associated with performance for three pistol and two rifle shooters.

With the exception of aim point accuracy in the pistol-shooting group, no relationships could be confidently established from the group based rifle and pistol group data. While there were indications that strong relationships may exist, these relationships were influenced considerably by one or two shooters. As such, more work with a greater number of subjects would be required to substantiate these relationships. Further, more thorough examination of the aim point to identify strategies may assist with this work.

6.2.2.3 Body sway and aim point fluctuation

Body sway and aim point fluctuation were related for most pistol and rifle shooters. All rifle shooters and three of the five pistol shooters showed an association between body sway and aim point fluctuation significant at $p<0.05$.

This relationship was different for different individuals in terms of degree and direction of association, parameters associated and the time period of importance.

Four of the rifle shooters and the three pistol shooters showed an increase in body sway was associated with an increase in aim point fluctuation, as expected.

Two rifle shooters showed an increase in body sway was associated with a decrease in aim point fluctuation. It may be for these shooters that an optimal amount of body sway exists, and further reduction of this sway is detrimental to the shooter's ability to hold the aim point steady.
All six rifle shooters showed both the expected X-X and Y-Y associations between body sway and aim point fluctuation, as well as the surprising X-Y and Y-X associations. It may be that these relationships are general, indicating only that an association exists between body sway and aim point fluctuation, or it may indicate that

an association exists between body sway in one axis and aim point fluctuation in the other.

One pistol shooter showed X-X associations while one showed Y-X associations between body sway and aim point fluctuation.

Due to the small number of shooters in this study, more research is required to better define this relationship for elite shooters. This work needs a more thorough examination of aim point strategies and analysis of time lag between body sway and aim point fluctuation. Also, kinematic analysis will provide information that may assist in establishing the causes of the X-Y, Y-X associations evident in most shooters in this study.

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APPENDIX A

Proofs: 16-bit error propagation due to quantisation in data obtained using the AMTI LG6-4 and Kistler 9287A force plates

AMTI Force Plate

Type AMTI LG6-4

16 bit ADC

Gain: 4000 (maximum setting on AMTI SGA6-4 amplifiers)

Dimensions: 610mm X 1220mm

Table A.1: Minimum increment of measure, error and example values for AMTI LG6-4 force plate

	Minimum measurement (N / Nm)	Measurement error (± N, ± Nm)	Measured values (N / Nm)
Fx	**0.0231**	**± 0.0116**	**2**
Fy	**0.0231**	**± 0.0116**	**1**
Fz	**0.0888**	**± 0.0444**	**750**
Mx	**0.0213**	**± 0.0106**	**24**
My	**0.0150**	**± 0.0075**	**55**

Table A.1 shows values used in error approximations. Minimum measurements are the steps in which each channel is measured for the AMTI LG6-4 force plate. These values are based on transducer sensitivities, amplifier gain settings and 16 bit ADC. The measured values are taken from a pistol shooting trial completed during testing and are typical of values obtained for other trials.

Uncertainty for COPx:

*Let (Fx * Dz) = A*

The value of A, using the values from Table A.1 is:

$$A = Fx * Dz$$

$$A = 2 * -0.0535$$

$$A = -0.428 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fx| * Dz$$

$$|\delta A| \leq 0.0116 * 0.0535$$

$$|\delta A| \leq 0.0006 \text{ Nm}$$

*Let - My + (Fx * Dz) = B*

The value of B, using the values from Table A.1 is:

$$B = -My + A$$

$$B = -55 + -0.428$$

$$B = -55.428 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta My| + |\delta A|$$

$$|\delta B| \leq 0.0075 + 0.0006$$

$$|\delta B| \leq 0.0081 \text{ Nm}$$

The value of COPx, using the values from Table A.1:

$$COPx = \frac{-My + (Fx * Dz)}{Fz}$$

From previous definition, *- My + (Fx * Dz) = B*

$$COPx = \frac{B}{Fz}$$

$$COPx = \frac{-55.428}{750}$$

$$COPx = -0.07348m$$

Error associated with COPx:

$$\left|\frac{\delta COPx}{COPx}\right| \leq \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

From Table A.1 $\delta Fz = 0.0444N$ and $Fz = 750N$

$$\left|\frac{\delta COPx}{COPx}\right| \leq \left|\frac{0.0081}{-55.428}\right| + \left|\frac{0.0444}{750}\right|$$

$$\left|\frac{\delta COPx}{COPx}\right| \leq 0.015\% + 0.006\% \leq 0.021\%$$

So there is an error of approximately 0.021% in COPx calculations due to quantisation error for the given values of force and moment data.

Thus

$$COPx = -0.07348m \pm 0.000015m$$

or

$$\boxed{COPx = -73.48\ mm \pm 0.02mm}$$

Uncertainty for COPy

*Let (Fy * Dz) = A*

The value of A, using the values from Table A.1 is:

$$A = Fy * Dz$$

$$A = 1 * -0.0535$$

$$A = -0.0535\ Nm$$

Error associated with A:

$$|\delta A| \leq |\delta Fy| * Dz$$

$$|\delta A| \leq 0.0116 * 0.0535$$

$$|\delta A| \leq 0.0006\ Nm$$

*Let Mx + (Fy * Dz) = B*

The value of B, using the values from Table A.1 is:

$$B = Mx + A$$

$$B = 24\ Nm + -0.0535$$

$$B = 23.9465\ Nm$$

Error associated with B:

$$|\delta B| \leq |\delta Mx| + |\delta A|$$

$$|\delta B| \leq 0.0106 + 0.0006$$

$$|\delta B| \leq 0.0112\ Nm$$

The value of COPy, using the values from Table A.1:

$$COPy = \frac{Mx + (Fy * Dz)}{Fz}$$

From previous definition, *Mx + (Fy * Dz) = B*

$$COPy = \frac{B}{Fz}$$

$$COPy = \frac{24.0535}{750}$$

$$COPy = 0.03207m$$

Error associated with COPy:

$$\left|\frac{\delta COPy}{COPy}\right| \leq \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

From Table A.1, δFz = 0.0444 and Fz = 750N

$$\left|\frac{\delta COPy}{COPy}\right| \leq \left|\frac{0.0112}{24.0535}\right| + \left|\frac{0.0444}{750}\right|$$

$$\left|\frac{\delta COPy}{COPy}\right| \leq 0.047\% + 0.006\% \leq 0.053\%$$

So there is an uncertainty of approximately 0.05% in COPy calculations due to quantisation error for the given values of force and moment data.

Thus

$$\text{COPy} = 0.003207\text{m} \pm 0.000017\text{m}$$

or

$$\boxed{\text{COPy} = 32.07\text{ mm} \pm 0.02\text{mm}}$$

KISTLER Force Plate

Type Kistler 9287A

16 bit ADC

Range: $Fz = 500N$

Range: $Fx, Fy = 200N$

Dimensions 600mm X 900 mm

Table A.2: Minimum increment of measure, error and example values for KISTLER force plate

	Minimum measurement (N)	Measurement error (± N)	Measured values (N)
Fz1	**0.0153**	**0.0076**	**187**
Fz2	**0.0153**	**0.0076**	**222**
Fz3	**0.0153**	**0.0076**	**291**
Fz4	**0.0153**	**0.0076**	**50**
Fy1	**0.0061**	**0.0031**	**0.5**
Fy2	**0.0061**	**0.0031**	**0.5**
Fx1	**0.0061**	**0.0031**	**1**
Fx2	**0.0061**	**0.0031**	**1**

NB (manufacturer specified and assumed constant for this analysis)

a = 0.200 m (distance from y axis to transducer axis)

b = 0.350 m (distance from x axis to transducer axis)

Dz = -0.045 m

Error associated with COPx:

The moment about the Y axis (My) is calculated by:

$$My = a * (-Fz1 + Fz2 + Fz3 - Fz4)$$

Using values from Table A.4:

$$My = 0.200 * (-Fz1 + Fz2 + Fz3 - Fz4)$$

$$My = 0.200 * (-187 + 222 + 291 - 50)$$

$$My = 55 \text{ Nm}$$

Error associated with My:

$$|\delta My| \leq a * (|\delta Fz1 + |\delta Fz2| + |\delta Fz3| + |\delta Fz4|)$$

$$|\delta My| \leq 0.200 * (0.0076 + 0.0076 + 0.0076 + 0.0076)$$

$$|\delta My| \leq 0.0061 \text{ Nm}$$

Total force along the x axis (Fx) is calculated by:

$$Fx = Fx1 + Fx2$$

Using values from Table A.4:

$$Fx = 1 + 1$$

$$Fx = 2 \text{ N}$$

Error associated with Fx:

$$|\delta Fx| \leq |\delta Fx1| + |\delta Fx2|$$

$$|\delta Fx| \leq 0.0031 + 0.0031$$

$$|\delta Fx| \leq 0.0062$$

*Let (Fx * Dz) = A*

Using values from Table A.4:

$$A = 2 * -0.045$$

$$A = -0.09 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fx| * Dz$$

$$|\delta A| \leq 0.0062 * 0.045$$

$$|\delta A| \leq 0.0003$$

*Let My - (Fx * Dz) = B*

Using values from Table A.4:

$$B = -My + A$$

$$B = -55 + -0.09$$

$$B = -55.09 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta My| + |\delta A|$$

$$|\delta B| \leq 0.00061 + 0.0003$$

$$|\delta B| \leq 0.0064 \text{ Nm}$$

The value of COPx, using the values from Table A.4:

$$COPx = \frac{-My + (Fx * Dz)}{Fz}$$

From previous definition, -My + (Fx * Dz) = B

$$COPx = \frac{B}{Fz}$$

$$COPx = \frac{-55.09}{750}\,m$$

$$COPx = -0.07345m$$

Error associated with COPx:

$$\left|\frac{\delta COPx}{COPx}\right| \leq \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

$$\left|\frac{\delta COPx}{COPx}\right| \leq \left|\frac{0.0064}{-55.09}\right| + \left|\frac{0.0305}{750}\right|$$

$$\left|\frac{\delta COPx}{COPx}\right| \leq 0.012\% + 0.004\% \leq 0.016\%$$

Thus

$$COPx = -0.07345m \pm 0.000012m$$

or

$$\boxed{COPx = -73.45\ mm \pm 0.01mm}$$

Error associated with COPy:

The moment about the X axis (Mx) is calculated by:

$$Mx = b * (Fz1 + Fz2 - Fz3 - Fz4)$$

Using values from Table A.4:

$$Mx = 0.350 * (Fz1 + Fz2 - Fz3 - Fz4)$$

$$Mx = 0.350 * (187 + 222 - 291 - 50)$$

$$Mx = 24\ Nm$$

Error associated with Mx:

$$|\delta Mx| \leq b * (|\delta Fz1|+|\delta Fz2|+|\delta Fz3|+|\delta Fz4|)$$

$$|\delta Mx| \leq 0.350 * (0.0076 + 0.0076 + 0.0076 + 0.0076)$$

$$|\delta Mx| \leq 0.0107\ Nm$$

Total force along the y axis (Fy) is calculated by:

$$Fy = Fy1 + Fy2$$

Using values from Table A.4:

$$Fy = 0.5 + 0.5$$

$$Fy = 1 \text{ N}$$

Error associated with Fy:

$$|\delta Fy| \leq |\delta Fy1| + |\delta Fy2|$$

$$|\delta Fy| \leq 0.0031 + 0.0031$$

$$|\delta Fy| \leq 0.0062 \text{ N}$$

*Let (Fy * Dz) = A*

Using values from Table A.4:

$$A = 1 * -0.045$$

$$A = -0.045 \text{ Nm}$$

Error associated with A:

$$|\delta A| \leq |\delta Fy| * Dz$$

$$|\delta A| \leq 0.0062 * 0.045$$

$$|\delta A| \leq 0.0003 \text{ Nm}$$

*Let Mx - (Fy * Dz) = B*

Using values from Table A.4:

$$B = Mx - A$$

$$B = 24 - (-0.045)$$

$$B = 24.045 \text{ Nm}$$

Error associated with B:

$$|\delta B| \leq |\delta Mx| + |\delta A|$$

$$|\delta B| \leq 0.0107 + 0.0003$$

$$|\delta B| \leq 0.0110 \text{ Nm}$$

The value of COPy, using the values from Table A.4:

$$COPy = \frac{Mx - (Fy * Dz)}{Fz}$$

From previous definition, Mx - (Fy * Dz) = B

$$COPy = \frac{B}{Fz}$$

$$COPy = \frac{24.045}{750}\,m$$

$$COPy = 0.03206m$$

Error associated with COPy:

$$\left|\frac{\delta COPy}{COPy}\right| \le \left|\frac{\delta B}{B}\right| + \left|\frac{\delta Fz}{Fz}\right|$$

$$\left|\frac{\delta COPy}{COPy}\right| \le \left|\frac{0.0010}{24.045}\right| + \left|\frac{0.0305}{750}\right|$$

$$\left|\frac{\delta COPy}{COPy}\right| \le 0.046\% + 0.004\% \le 0.050\%$$

Thus

$$\text{COPy} = 0.03206\text{m} \pm 0.0000115\text{m}$$

or

$$\boxed{\text{COPy} = 32.06\text{ mm} \pm 0.01\text{ mm}}$$

APPENDIX B

Proofs: 12 bit error propagation due to quantisation and measurement step in parameters calculated from data obtained using the AMTI LG6-4 force plate

Note:
For all calculations, Fz = 750N.
Error values for single COP measures are as for a shooter of 750N (reported in section 5.1.1.1.1)
Max = Maximum
Min = Minimum

Horizontal Forces

FxRange = Fx (max) - Fx (min)

The quantisation step of Fx is 0.37N, or +/- 0.185N.

$$\delta(\text{FxRange}) = \sqrt{(\delta Fx(\max))^2 + (\delta Fx(\min))^2}$$

$$= \sqrt{(0.185)^2 + (0.185)^2} \qquad = \mathbf{0.262N}$$

and will certainly be no more than

$$\delta(\text{FxRange}) \leq \delta\text{Fx (max)} + \delta\text{Fx (min)}$$

$$\leq 0.185 + 0.185 \qquad \leq \mathbf{0.370N}$$

FyRange

As the quantisation step for Fy is also 0.37N, δFy will be the same as δFx.

$$\delta\text{FyRange} \qquad = \mathbf{0.262N}$$

$$\leq \mathbf{0.370}$$

FxSD

The standard deviation of Fx is calculated by:

$$\text{FxSD} = \sqrt{\frac{\sum (Fx - \bar{Fx})^2}{n - 1}}$$

Where Fx = value of Fx for n samples

$\bar{Fx}$ = mean of all Fx values

n = number of samples

The approximate error due to quantisation will be:

For n = 128 (1s)

Let A = $(Fx - \bar{Fx})^2$

δA = 2 * $(\delta Fx + \delta\bar{Fx})$

where δFx = 0.185N (from table 5.1.1.1)

and, using the process outlined in the averages paragraph above

approximate $\delta\bar{Fx}$ 1s $= \dfrac{\sqrt{0.185^2 * 128}}{127}$ = 0.016N

δA = 2 * (0.185 + 0.016) = 0.403

Let B = $\sum (Fx - \bar{Fx})^2 = \sum$ (A)

δB = $\sum\delta$A $= \sqrt{0.185^2 * 128}$ (using quadrature) = 4.556

Let C $= \dfrac{\sum (Fx - \bar{Fx})^2}{n-1} = \dfrac{B}{n-1}$

δC = δB * $\dfrac{1}{n-1}$ = 4.556 * $\dfrac{1}{128-1}$ = 0.036

$$\text{FxSD} = \sqrt{\frac{\sum (Fx - \bar{Fx})^2}{n - 1}} = \sqrt{C}$$

δFxSD = $\dfrac{1}{2}$ * δC = $\dfrac{1}{2}$ * 0.036 **= 0.018N**

For n = 384 (3s)

Let A = $(Fx - \bar{F}x)^2$

δA $= 2 * (\delta Fx + \delta\bar{F}x)$

where δFx = 0.185N (from table 5.1.1.1)

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta\bar{F}x \text{ 3s} = \frac{\sqrt{0.185^2 * 384}}{383} = 0.009\text{N}$$

δA = 2 * (0.185 + 0.009) = 0.389

Let B = $\sum (Fx - \bar{F}x)^2 = \sum (A)$

δB = $\sum\delta$A $= \sqrt{0.185^2 * 384}$ (using quadrature) = 7.620

Let C = $\dfrac{\sum(Fx - \bar{F}x)^2}{n-1} = \dfrac{B}{n-1}$

δC = δB * $\dfrac{1}{n-1}$ = 7.620 * $\dfrac{1}{384-1}$ = 0.020

$$\text{FxSD} = \sqrt{\frac{\sum (Fx - \bar{F}x)^2}{n - 1}} = \sqrt{C}$$

δFxSD = $\dfrac{1}{2}$ * δC = $\dfrac{1}{2}$ * 0.020 **= 0.010N**

For n = 640 (5s)

Let A = $(Fx - \bar{F}x)^2$

δA $= 2 * (\delta Fx + \delta\bar{F}x)$

where δFx = 0.185N (from table 5.1.1.1)

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta\bar{F}x \text{ 5s} = \frac{\sqrt{0.185^2 * 640}}{639} = 0.007\text{N}$$

$$\delta A = 2 * (0.185 + 0.007) = 0.385$$

Let B $= \sum (Fx - \bar{F}x)^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{0.185^2 * 640} \text{ (using quadrature)} = 9.730$$

Let C $= \dfrac{\sum (Fx - \bar{F}x)^2}{n-1} = \dfrac{B}{n-1}$

$$\delta C = \delta B * \frac{1}{n-1} = 9.730 * \frac{1}{640-1} = 0.015$$

FxSD $= \sqrt{\dfrac{\sum (Fx - \bar{F}x)^2}{n - 1}} = \sqrt{C}$

$$\delta FxSD = \frac{1}{2} * \delta C = \frac{1}{2} * 0.015 \qquad \mathbf{= 0.008N}$$

and will be no more than:

For n = 128 (1s)

Let A = $(Fx - \bar{F}x)^2$

$$\delta A \leq 2 * (\delta Fx + \delta\bar{F}x)$$

where δFx = 0.185N (from table 5.1.1)

and, using the process outlined in the averages paragraph above

maximum $\delta\bar{F}x$ (simply the error of a single measure)

$\leq$ 0.185N

$$\delta A \leq 2 * (0.185 + 0.185) \leq 0.740$$

Let B $= \sum (Fx - \bar{F}x)^2 = \sum (A)$

$\delta B \leq \sum \delta A \leq 0.740 * 128 \leq 94.72$

Let C $= \dfrac{\sum (Fx - \bar{F}x)^2}{n-1} = \dfrac{B}{n-1}$

$\delta C \leq \delta B * \dfrac{1}{n-1} \leq 94.72 * \dfrac{1}{128-1} \leq 0.746$

FxSD $= \sqrt{\dfrac{\sum (Fx - \bar{F}x)^2}{n - 1}} = \sqrt{C}$

$\delta FxSD \leq \dfrac{1}{2} * \delta C \leq \dfrac{1}{2} * 0.746$ $\leq$ **0.373N**

For n = 384 (3s)

Let A = $(Fx - \bar{F}x)^2$

$\delta A \leq 2 * (\delta Fx + \delta\bar{F}x)$

where $\delta Fx = 0.185N$ (from table 5.1.1.1)

and, using the process outlined in the averages paragraph above

maximum $\delta\bar{F}x$ (simply the error of a single measure)

$\leq 0.185N$

$\delta A \leq 2 * (0.185 + 0.185) \leq 0.740$

Let B $= \sum (Fx - \bar{F}x)^2 = \sum (A)$

$\delta B \leq \sum \delta A \leq 0.740 * 384 \leq 284.16$

Let C $= \dfrac{\sum (Fx - \bar{F}x)^2}{n-1} = \dfrac{B}{n-1}$

$\delta C \leq \delta B * \dfrac{1}{n-1} \leq 284.16 * \dfrac{1}{384-1} \leq 0.742$

$$\text{FxSD} = \sqrt{\frac{\sum (Fx - \bar{F}x)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{FxSD} \leq \frac{1}{2} * \delta\text{C} \leq \frac{1}{2} * 0.742 \qquad \mathbf{\leq 0.371N}$$

For n = 640 (5s)

Let A = $(Fx - \bar{F}x)^2$

$$\delta\text{A} \leq 2 * (\delta Fx + \delta\bar{F}x)$$

where $\delta\text{Fx} = 0.185\text{N}$ (from table 5.1.1.1)

and, using the process outlined in the averages paragraph above

maximum $\delta\bar{F}x$ (simply the error of a single measure)

$\leq 0.185\text{N}$

$$\delta\text{A} \leq 2 * (0.185 + 0.185) \leq 0.740$$

Let B $= \sum (Fx - \bar{F}x)^2 = \sum(\text{A})$

$$\delta\text{B} \leq \sum\delta\text{A} \leq 0.740 * 640 \leq 473.600$$

Let C $= \dfrac{\sum(Fx - \bar{F}x)^2}{n-1} = \dfrac{B}{n-1}$

$$\delta\text{C} \leq \delta\text{B} * \frac{1}{n-1} \leq 473.600 * \frac{1}{640-1} \leq 0.741$$

$$\text{FxSD} = \sqrt{\frac{\sum (Fx - \bar{F}x)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{FxSD} \leq \frac{1}{2} * \delta\text{C} \leq \frac{1}{2} * 0.741 \qquad \mathbf{\leq 0.371N}$$

FySD

As Fy is measured in the same steps as Fx, the error will be the same.

δFySD (1s) $= \mathbf{0.038N}$

$\leq \mathbf{0.373N}$

δFySD (3s) $= \mathbf{0.022N}$

$\leq \mathbf{0.371N}$

δFySD (5s) $= \mathbf{0.017N}$

$\leq \mathbf{0.371N}$

COPxRange = COPx (max) - COPx (min)

From previous calculations, δCOPx = 0.243mm

$$\delta\text{COPxRange} = \sqrt{(\delta COPx(\max))^2 + (\delta COPx(\min))^2}$$

$$= \sqrt{(0.243)^2 + (0.243)^2} \qquad = \mathbf{0.344mm}$$

and will be no greater than

$$\delta\text{COPxRange} \leq \delta\text{COPx (max)} + \delta\text{COPx (min)}$$

$$\leq 0.243 + 0.243 \qquad \leq \mathbf{0.486mm}$$

COPyRange = COPy (max) - COPy (min)

From previous calculations, δCOPy = 0.270mm

$$\delta\text{COPyRange} = \sqrt{(\delta COPy(\max))^2 + (\delta COPy(\min))^2}$$

$$= \sqrt{(0.270)^2 + (0.270)^2} \qquad = \mathbf{0.382\ mm}$$

and will be no greater than

$$\delta\text{COPyRange} \leq \delta\text{COPy (max)} + \delta\text{COPy (min)}$$

$\leq$ 0.270 + 0.270 **$\leq$ 0.540 mm**

COPAbsRange $= \sqrt{(COPx)^2 + (COPy)^2}$

δCOPAbsRange = 0.5 * ((2 * δCOPxRange) + (2 * δCOPyRange))

Using values calculated above for δCOPxRange and δCOPyRange

δCOPAbsRange = 0.5 * ((2 * 0.344) + (2 * 0.372)) **= 0.716 mm**

and will be no greater than

$\leq$ 0.5 * ((2 * 0.486) + (2 * 0.540)) **$\leq$ 1.026 mm**

COPxSD

The standard deviation of COPx is calculated by:

$$\text{COPxSD} = \sqrt{\frac{\sum (COPx - C\bar{O}Px)^2}{n - 1}}$$

Where COPx = value of COPx for 1 to n samples

$C\bar{O}Px$ = mean of all COPx values

n = number of samples

Approximate error due to quantisation will be:

For n = 128 (1s)

Let A = $(COPx - C\bar{O}Px)^2$

δA $= 2 * (\delta COPx + \delta C\bar{O}Px)$

where δCOPx (from calculations in section 5.1.1.1)

= 0.243mm

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta C\bar{O}Px \text{ 1s} = \frac{\sqrt{0.243^2 * 128}}{128} = 0.021 \text{ mm}$$

$$\delta A = 2 * (0.243 + 0.021) = 0.529$$

Let B $= \sum (COPx - C\bar{O}Px)^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{0.529^2 * 128} \text{ (using quadrature)} = 5.984$$

Let C $= \dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1} = \dfrac{B}{n-1}$

$$\delta C = \delta B * \frac{1}{n-1} = 5.984 * \frac{1}{128-1} = 0.047$$

$$\text{COPxSD} = \sqrt{\frac{\sum (COPx - C\bar{O}Px)^2}{n - 1}} = \sqrt{C}$$

$$\delta \text{COPxSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 0.047 \qquad \mathbf{= 0.024 \text{ mm}}$$

For n = 384 (3s)

Let A = $(COPx - C\bar{O}Px)^2$

$$\delta A = 2 * (\delta COPx + x)$$

where δCOPx (from calculations in section 5.1.1.1)

= 0.243mm

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta C\bar{O}PX \text{ 3s} = \frac{\sqrt{0.243^2 * 384}}{384} = 0.012 \text{ mm}$$

$$\delta A = 2 * (0.243 + 0.012) = 0.511$$

Let B $= \sum (COPx - C\bar{O}Px)^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{0.511^2 * 384} \text{ (using quadrature)} = 10.010$$

Let C $= \dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C = \delta B * \dfrac{1}{n-1} = 10.010 * \dfrac{1}{384-1} = 0.026$

COPxSD $= \sqrt{\dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1}} = \sqrt{C}$

$\delta COPxSD = \dfrac{1}{2} * \delta C = \dfrac{1}{2} * 0.026$ **= 0.013 mm**

For n = 640 (5s)

Let A = $(COPx - C\bar{O}Px)^2$

$\delta A = 2 * (\delta COPx + \delta C\bar{O}Px)$

where $\delta COPx$ (from calculations in section 5.1.1.1)

= 0.243mm

and, using the process outlined in the averages paragraph above

approximate $\delta C\bar{O}Px$ 5s $= \dfrac{\sqrt{0.243^2 * 640}}{640} = 0.010$ mm

$\delta A = 2 * (0.243 + 0.010) = 0.505$

Let B $= \sum (COPX - C\bar{O}PX)^2 = \sum$ (A)

$\delta B = \sum \delta A = \sqrt{0.505^2 * 640}$ (using quadrature) = 12.781

Let C $= \dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C = \delta B * \dfrac{1}{n-1} = 12.781 * \dfrac{1}{640-1} = 0.020$

COPxSD $= \sqrt{\dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1}} = \sqrt{C}$

$$\delta\text{COPxSD} = \frac{1}{2} * \delta\text{C} = \frac{1}{2} * 0.020 \qquad = \mathbf{0.010\ mm}$$

And will be no more than

For n = 128 (1s)

Let A = $(COPx - C\bar{O}Px)^2$

$$\delta\text{A} \leq 2 * (\delta COPx + \delta C\bar{O}Px)$$

where δCOPx (from calculations in section 5.1.1.1)

$\leq$ 0.243mm

and, using the process outlined in the averages paragraph above

maximum $\delta C\bar{O}Px$ (simply the error of a single measure)

$\leq$ 0. 243 mm

$$\delta\text{A} \leq 2 * (0.243 + 0.243) \leq 0.972$$

Let B $= \sum (COPx - C\bar{O}Px)^2 = \sum(\text{A})$

$$\delta\text{B} \leq \sum\delta\text{A} \leq 0.972 * 128 \leq 124.416$$

$$\text{Let C} = \frac{\sum (COPx - C\bar{O}Px)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta\text{C} \leq \delta\text{B} * \frac{1}{n-1} \leq 124.416 * \frac{1}{128-1} \leq 0.980$$

$$\text{COPxSD} = \sqrt{\frac{\sum (COPx - C\bar{O}Px)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPxSD} \leq \frac{1}{2} * \delta\text{C} \leq \frac{1}{2} * 0.980 \qquad \leq \mathbf{0.490\ mm}$$

For n = 384 (3s)

Let A = $(COPx - C\bar{O}Px)^2$

$\delta A \quad \leq 2 * (\delta COPx + \delta C\bar{O}Px)$

where δCOPx (from calculations in section 5.1.1.1)

$\leq$ 0.243mm

and, using the process outlined in the averages paragraph above

maximum $\delta C\bar{O}PX$ (simply the error of a single measure)

$\leq$ 0. 243 mm

$\delta A \quad \leq 2 * (0.243 + 0.243) \quad \leq 0.972$

Let B $= \sum (COPx - C\bar{O}Px)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 0.972 * 384 \quad \leq 373.248$

Let C $= \dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C \quad \leq \delta B * \dfrac{1}{n-1} \quad \leq 373.248 * \dfrac{1}{384-1} \quad \leq 0.975$

COPxSD $= \sqrt{\dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1}} = \sqrt{C}$

$\delta COPxSD \leq \dfrac{1}{2} * \delta C \quad \leq \dfrac{1}{2} * 0.975$ $\quad \leq$ **0.487 mm**

For n = 640 (5s)

Let A = $(COPx - C\bar{O}Px)^2$

$\delta A \quad \leq 2 * (\delta COPx + \delta C\bar{O}Px)$

where δCOPx (from calculations in section 5.1.1.1)

$\leq$ 0.243mm

and, using the process outlined in the averages paragraph above

maximum $\delta C\bar{O}Px$ (simply the error of a single measure)

$\leq$ 0. 243 mm

$\delta A \quad \leq 2 * (0.243 + 0.243) \quad \leq 0.972$

Let B $= \sum (COPx - C\bar{O}Px)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 0.972 * 640 \quad \leq 622.080$

Let C $= \dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C \quad \leq \delta B * \dfrac{1}{n-1} \quad \leq 622.080 * \dfrac{1}{640-1} \quad \leq 0.974$

COPxSD $= \sqrt{\dfrac{\sum (COPx - C\bar{O}Px)^2}{n - 1}} = \sqrt{C}$

δCOPxSD $\leq \dfrac{1}{2} * \delta C \quad \leq \dfrac{1}{2} * 0.974 \quad \leq$ **0.487 mm**

COPySD

The standard deviation of COPx is calculated by:

$$\text{COPySD} = \sqrt{\frac{\sum (COPy - C\bar{O}Py)^2}{n - 1}}$$

Where COPy = value of COPy for n samples

$C\bar{O}Py$ = mean of all COPy values

n = number of samples

Approximate error due to quantisation will be:

For n = 128 (1s)

Let A = $(COPy - C\bar{O}Py)^2$

$\delta A = 2 * (COPy - C\bar{O}Py)^2$

where $\delta COPy$ (from calculations in section 5.1.1.1)

$= 0.270mm$

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta C\bar{O}Py \text{ 1s} = \frac{\sqrt{0.270^2 * 128}}{128} = 0.024 \text{ mm}$$

$\delta A = 2 * (0.270 + 0.024) = 0.588$

Let $B = \sum (COPy - C\bar{O}Py)^2 = \sum (A)$

$\delta B = \sum \delta A = \sqrt{0.588^2 * 128}$ (using quadrature) $= 6.694$

$$\text{Let } C = \frac{\sum (COPy - C\bar{O}Py)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta C = \delta B * \frac{1}{n-1} = 6.694 * \frac{1}{128-1} = 0.052$$

$$COPySD = \sqrt{\frac{\sum (COPy - C\bar{O}Py)^2}{n - 1}} = \sqrt{C}$$

$\delta COPySD = \frac{1}{2} * \delta C = \frac{1}{2} * 0.052$ **= 0.026 mm**

For n = 384 (3s)

Let $A = (COPy - C\bar{O}Py)^2$

$\delta A = 2 * (COPy - C\bar{O}Py)^2$

where $\delta COPy$ (from calculations in section 5.1.1.1)

$= 0.270mm$

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta C\bar{O}Py \text{ 3s} = \frac{\sqrt{0.270^2 * 384}}{384} = 0.014 \text{ mm}$$

$$\delta A = 2 * (0.270 + 0.014) = 0.568$$

$$\text{Let B} = \sum (COPy - C\bar{O}Py)^2 = \sum (A)$$

$$\delta B = \sum \delta A = \sqrt{0.568^2 * 384} \text{ (using quadrature)} = 11.122$$

$$\text{Let C} = \frac{\sum (COPy - C\bar{O}Py)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta C = \delta B * \frac{1}{n-1} = 11.122 * \frac{1}{384-1} = 0.029$$

$$\text{COPySD} = \sqrt{\frac{\sum (COPy - C\bar{O}Py)^2}{n - 1}} = \sqrt{C}$$

$$\delta \text{COPySD} = \frac{1}{2} * \delta C = \frac{1}{2} * 0.029 \qquad \mathbf{= 0.015 \text{ mm}}$$

For n = 640 (5s)

Let A = $(COPy - C\bar{O}Py)^2$

$$\delta A = 2 * (COPy - C\bar{O}Py)^2$$

where δCOPy (from calculations in section 5.1.1.1)

= 0.270mm

and, using the process outlined in the averages paragraph above

$$\text{approximate } \delta C\bar{O}Py \text{ 5s} = \frac{\sqrt{0.270^2 * 640}}{640} = 0.011 \text{ mm}$$

$$\delta A = 2 * (0.270 + 0.011) = 0.561$$

$$\text{Let B} = \sum (COPy - C\bar{O}Py)^2 = \sum (A)$$

$$\delta B = \sum \delta A = \sqrt{0.561^2 * 640} \text{ (using quadrature)} = 14.201$$

Let C $= \dfrac{\sum (COPy - C\bar{O}Py)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C = \delta B * \dfrac{1}{n-1} = 14.201 * \dfrac{1}{640-1} = 0.022$

COPySD $= \sqrt{\dfrac{\sum (COPy - C\bar{O}Py)^2}{n - 1}} = \sqrt{C}$

$\delta COPySD = \dfrac{1}{2} * \delta C = \dfrac{1}{2} * 0.022$ **= 0.011 mm**

And will be no more than

For n = 128 (1s)

Let A = $(COPy - C\bar{O}Py)^2$

$\delta A \le 2 * (COPy - C\bar{O}Py)^2$

where $\delta COPy$ (from calculations in section 5.1.1.1)

≤ 0.270mm

and, using the process outlined in the averages paragraph above

maximum $\delta C\bar{O}Py$ (simply the error of a single measure)

≤ 0.270 mm

$\delta A \le 2 * (0.270 + 0.270) \le 1.080$

Let B $= \sum (COPy - C\bar{O}Py)^2 = \sum (A)$

$\delta B \le \sum \delta A \le 1.080 * 128 \le 138.240$

Let C $= \dfrac{\sum (COPy - C\bar{O}Py)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C \le \delta B * \dfrac{1}{n-1} \le 138.240 * \dfrac{1}{128-1} \le 1.089$

COPySD $= \sqrt{\dfrac{\sum (COPy - C\bar{O}Py)^2}{n - 1}} = \sqrt{C}$

δCOPySD $\leq \dfrac{1}{2} * \delta C \quad \leq \dfrac{1}{2} * 1.089 \quad \leq$ **0.544 mm**

For n = 384 (3s)

Let A = $(COPy - C\bar{O}Py)^2$

$\delta A \quad \leq 2 * (COPy - C\bar{O}Py)$

where δCOPy (from calculations in section 5.1.1.1)

$\leq$ 0.270mm

and, using the process outlined in the averages paragraph above

maximum $\delta C\bar{O}Py$ (simply the error of a single measure)

$\leq$ 0. 270 mm

$\delta A \quad \leq 2 * (0.270 + 0.270) \quad \leq 1.080$

Let B $= \sum (COPy - C\bar{O}Py)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 1.080 * 384 \quad \leq 414.720$

Let C $= \dfrac{\sum (COPy - C\bar{O}Py)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C \quad \leq \delta B * \dfrac{1}{n-1} \quad \leq 414.720 * \dfrac{1}{384-1} \quad \leq 1.083$

COPySD $= \sqrt{\dfrac{\sum (COPy - C\bar{O}Py)^2}{n - 1}} = \sqrt{C}$

δCOPySD $\leq \dfrac{1}{2} * \delta C \quad \leq \dfrac{1}{2} * 1.083 \quad \leq$ **0.541 mm**

For n = 640 (5s)

Let A = $(COPy - C\bar{O}Py)^2$

δA $\leq 2 * (COPy - C\bar{O}Py)^2$

where δCOPy (from calculations in section 5.1.1.1)

$\leq$ 0.270mm

and, using the process outlined in the averages paragraph above

maximum $\delta C\bar{O}PY$ (simply the error of a single measure)

$\leq$ 0. 270 mm

δA $\leq$ 2 * (0.270 + 0.270) $\leq$ 1.080

Let B = $\sum (COPy - C\bar{O}Py)^2 = \sum (A)$

δB $\leq \sum\delta$A $\leq$ 1.080 * 640 $\leq$ 691.200

$$\text{Let C} = \frac{\sum (COPy - C\bar{O}Py)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta C \leq \delta B * \frac{1}{n-1} \leq 691.200 * \frac{1}{640-1} \leq 1.082$$

$$\text{COPySD} = \sqrt{\frac{\sum (COPy - C\bar{O}Py)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPySD} \leq \frac{1}{2} * \delta C \leq \frac{1}{2} * 1.082 \leq \mathbf{0.541\ mm}$$

COPxLength

$$= \left(\sqrt{(COPx(2) - COPx(1))^2}\right) + \left(\sqrt{(COPx(3) - COPx(2))^2}\right) + \ldots..$$

$$. \quad \ldots.+ \left(\sqrt{(COPx(n) - COPx(n - 1))^2}\right)$$

Where

n = number of points in sample

COPx1, COPx2... = 1st, 2nd .... measured location of COPx

COPy1, COPy2... = 1st, 2nd .... measured location of COPy

As mentioned in the discussion above, the two extremes for COP length will be a straight line path in one direction and a stationary or constantly oscillating point.

The error for the case where the path moves in one direction only depends on the first and last point measured. Hence the error will be two times the error for one point.

$$\delta\text{COPxLength} = \sqrt{(\delta COPx(first))^2 + (\delta COPx(last))^2}$$

$$= \sqrt{(0.243)^2 + (0.243)^2} \qquad = \mathbf{0.344mm}$$

and will be no more than

$$\leq 0.243 + 0.243 \qquad \leq \mathbf{0.486mm}$$

For the case of a stationary or constantly oscillating point:

$$\delta\text{COPxLength} = \delta\text{COPxLength (single)} * (n-1)$$

where n = no. of samples (128, 384 and 640)

δCOPxLength (single)

= error for one length measurement between consecutive points

= 0.344 mm or ≤ 0.486 mm

Maximum possible error will be

1 second	≤ 0.486 * (128-1)	**≤ 61.772 mm**
3 seconds	≤ 0.486 * (384-1)	**≤ 186.138 mm**
5 seconds	≤ 0.486 * (640-1)	**≤ 310.554 mm**

The approximate error at any time will equal (using quadrature summation)

δCOPxLength 1 second $= \sqrt{0.344^2 \ * \ (128 - 1)} =$ **3.877 mm**

3 seconds $= \sqrt{0.344^2 \ * \ (384 - 1)}$ = **6.732 mm**

5 seconds $= \sqrt{0.344^2 \ * \ (640 - 1)}$ = **8.696 mm**

COPyLength

COPyLength is calculated in the same way COPxLength is calculated, but with COPy values substituted. The error for the case where the path moves in one direction only depend on the first and last point and will be two times the error for one point.

$$\delta\text{COPyLength} = \sqrt{(\delta COPy(first))^2 + (\delta COPy(last))^2}$$

$$= \sqrt{(0.270)^2 + (0.270)^2} = \mathbf{0.372mm}$$

and will be no more than

$$\leq 0.270 + 0.270 \qquad \leq \mathbf{0.540mm}$$

For the case of a stationary or constantly oscillating point:

δCOPyLength = δCOPyLength (single) * (n-1)

Where δCOPyLength (single)

= error for the distance between consecutive points

Maximum possible error will be

1 second $\leq$ 0.540 * (128-1) **$\leq$ 68.580 mm**

3 seconds $\leq$ 0.540 * (384-1) **$\leq$ 206.820 mm**

5 seconds $\leq$ 0.540 * (640-1) **$\leq$ 345.060 mm**

The approximate error at any time will equal (using quadrature summation)

δCOPyLength 1 second $= \sqrt{0.372^2 \ * \ (128 - 1)} =$ **4.192 mm**

3 seconds $= \sqrt{0.372^2 \ * \ (384 - 1)}$ = **7.280 mm**

$$5 \text{ seconds} \quad = \sqrt{0.372^2 * (640 - 1)} \quad = \mathbf{9.404\ mm}$$

COPAbsLength

The formula for calculating the length of COPAbs is:

$$\left(\sqrt{(COPx(2) - COPx(1))^2 + (COPy(2) - COPy(1))^2}\right) +$$

$$\left(\sqrt{(COPx(3) - COPx(2))^2 + (COPy(3) - COPy(2))^2}\right) + \ldots\ldots$$

$$\ldots\ldots + \left(\sqrt{(COPx(n) - COPx(n - 1))^2 + (COPy(n) - COPy(n - 1))^2}\right)$$

Where

n	= number of points in sample
COPx1, COPx2...	= 1st, 2nd ....nth measured location of COPx
COPy1, COPy2...	= 1st, 2nd .... nth measured location of COPy

The calculation for the displacement between two points is:

$$\left(\sqrt{(COPx(2) - COPx(1))^2 + (COPy(2) - COPy(1))^2}\right)$$

let C $= (COPx(2) - COPx(1))^2$

$$\delta C = 2 * \sqrt{\delta COPx(2)^2 + \delta COPx(1)^2}$$

$$= 2 * \sqrt{(0.243)^2 + (0.243)^2} \quad = 0.687 \text{ mm}$$

$$\leq 2 * (0.243 + 0.243) \quad \leq 0.972 \text{ mm}$$

let D $= (COPy(2) - COPy(1))^2$

$$\delta D = 2 * \sqrt{\delta COPy(2)^2 + \delta COPy(1)^2}$$

$$= 2 * \sqrt{(0.270)^2 + (0.270)^2} \quad = 0.764 \text{ mm}$$

$$\leq 2 * (0.270 + 0.270) \quad \leq 1.080 \text{ mm}$$

COPAbsLength (single) = the absolute distance between two consecutive points

$$= \left(\sqrt{(COPx(2) - COPx(1))^2 + (COPy(2) - COPy(1))^2} \right)$$

$$= \sqrt{C + D} = (C + D)^{1/2}$$

δCOPAbsLength (single) = 0.5 * (δC + δD)

= 0.5 * (0.687 + 0.764) **= 0.726 mm**

and will be no more than

≤ 0.5 * (0.972 + 1.080) **≤ 1.026 mm**

As for COPxLength and COPyLength, minimum potential error occurs when the COP describes a straight line traced during constant movement and is maximum when the trace constantly oscillates or is stationary.

The error for the case where the path moves in one direction only is the same as above.

δCOPAbsLength **= 0.726 mm**

≤ 1.020 mm

For the case of a stationary or constantly oscillating point:

δCOPAbsLength = δCOPAbsLength (single) * (n-1)

Maximum possible error will be

1 second	≤ 1.020 * (128-1)	**≤ 129.540 mm**
3 seconds	≤ 1.020 * (384-1)	**≤ 390.660 mm**
5 seconds	≤ 1.020 * (640-1)	**≤ 651.780 mm**

The approximate error at any time will equal (using quadrature summation)

1 second	$= \sqrt{0.726^2 * (128 - 1)}$	**= 8.001 mm**
3 seconds	$= \sqrt{0.726^2 * (384 - 1)}$	**= 13.895 mm**

$$5 \text{ seconds} = \sqrt{0.726^2 * (640 - 1)} = \mathbf{17.948\ mm}$$

COPxVelSD

The standard deviation of COPx speed is calculated by:

$$\text{COPxVelSD} = \sqrt{\frac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1}}$$

Where $COPxVel$ = value of COPX velocity for 1 to n samples

$CO\bar{P}xVel$ = mean of n COPX velocity values

n = number of samples

Approximate error due to quantisation will be

For n = 128 (1s)

Let A = $(COPxVel - CO\bar{P}xVel)^2$

$$\delta A = 2 * (COPxVel - CO\bar{P}xVel)$$

where $\delta COPxVel$ = 22.016 mm/s

and, using the process outlined in the averages paragraph above

$$\text{approximate } CO\bar{P}xVel \text{ 1s} = \frac{\sqrt{22.016^2 * 128}}{128} = 1.964 \text{ mm/s}$$

$$\delta A = 2 * (22.016 + 1.964) = 47.924$$

Let B $= \sum (COPxVel - CO\bar{P}xVel)^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{47.924^2 * 128} \text{ (using quadrature)} = 542.197$$

$$\text{Let C} = \frac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta C = \delta B * \frac{1}{n-1} = 542.197 * \frac{1}{128-1} = 4.269$$

$$\text{COPxVelSD} = \sqrt{\frac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPxVelSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 4.269 \qquad \mathbf{= 2.135\ mm/s}$$

For n = 384 (3s)

Let A = $(COPxVel - CO\bar{P}xVel)^2$

$$\delta A = 2 * (COPxVel - CO\bar{P}xVel)$$

where $\delta COPxVel$ = 22.016 mm/s

and, using the process outlined in the averages paragraph above

approximate $CO\bar{P}xVel$ 3s $= \dfrac{\sqrt{22.016^2 * 384}}{384}$ = 1.123 mm/s

$$\delta A = 2 * (22.016 + 1.123) = 46.279$$

Let B $= \sum (COPxVel - CO\bar{P}xVel)^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{46.279^2 * 384} \text{ (using quadrature)} = 906.879$$

Let C $= \dfrac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1} = \dfrac{B}{n-1}$

$$\delta C = \delta B * \frac{1}{n-1} = 906.879 * \frac{1}{384 - 1} = 2.368$$

$$\text{COPxVelSD} = \sqrt{\frac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPxVelSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 2.368 \qquad \mathbf{= 1.184\ mm/s}$$

For n = 640 (5s)

Let A = $(COPxVel - \overline{COPxVel})^2$

δA = 2 * $(COPxVel - \overline{COPxVel})$

where $\delta COPxVel$ = 22.016 mm/s

and, using the process outlined in the averages paragraph above

approximate $\overline{COPxVel}$ 5s = $\dfrac{\sqrt{22.016^2 * 640}}{640}$ = 0.870 mm/s

δA = 2 * (22.016 + 0.870) = 45.773

Let B = $\sum (COPxVel - \overline{COPxVel})^2 = \sum$ (A)

δB = $\sum\delta$A = $\sqrt{45.773^2 * 640}$ (using quadrature) = 1157.963

Let C = $\dfrac{\sum (COPxVel - \overline{COPxVel})^2}{n - 1} = \dfrac{B}{n-1}$

δC = δB * $\dfrac{1}{n-1}$ = 1157.963 * $\dfrac{1}{640 - 1}$ = 1.812

COPxVelSD = $\sqrt{\dfrac{\sum (COPxVel - \overline{COPxVel})^2}{n - 1}} = \sqrt{C}$

δCOPxVelSD = $\dfrac{1}{2}$ * δC = $\dfrac{1}{2}$ * 1.812 **= 0.906 mm/s**

And will be no more than

For n = 128 (1s)

Let A = $(COPxVel - \overline{COPxVel})^2$

δA $\leq$ 2 * $(COPxVel - \overline{COPxVel})$

where $\delta COPxVel$ $\leq$ 31.104 mm/s

and, using the process outlined in the averages paragraph above

maximum $CO\bar{P}xVel$ (simply the error of a single measure)

$\leq$ 31.104 mm/s

$\delta A \quad \leq 2 * (31.104 + 31.104) \leq 124.416$

Let B $= \sum (COPxVel - CO\bar{P}xVel)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 124.416 * 128 \quad \leq 15925.248$

Let C $= \dfrac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C \quad \leq \delta B * \dfrac{1}{n-1} \quad \leq 15925.248 * \dfrac{1}{128-1} \quad \leq 125.369$

COPxVelSD $= \sqrt{\dfrac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1}} = \sqrt{C}$

$\delta COPxVelSD \leq \dfrac{1}{2} * \delta C \quad \leq \dfrac{1}{2} * 125.369$ **$\leq$ 62.698 mm/s**

For n = 384 (3s)

Let A = $(COPxVel - CO\bar{P}xVel)^2$

$\delta A \quad \leq 2 * (COPxVel - CO\bar{P}xVel)$

where $\delta COPxVel$ $\leq$ 31.104 mm/s

and, using the process outlined in the averages paragraph above

maximum $CO\bar{P}xVel$ (simply the error of a single measure)

$\leq$ 31.104 mm/s

$\delta A \quad \leq 2 * (31.104 + 31.104) \leq 124.416$

Let B $= \sum (COPxVel - CO\bar{P}xVel)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \qquad \leq 124.416 \; * \; 384 \qquad \leq 47775.744$

$$\text{Let C} \;=\; \frac{\sum (COPxVel \;-\; CO\bar{P}xVel)^2}{n \;-\; 1} \;=\; \frac{B}{n-1}$$

$$\delta C \quad \leq \delta B \; * \; \frac{1}{n-1} \qquad \leq \; 47775.744 \; * \; \frac{1}{384 \;-\; 1} \quad \leq \; 124.741$$

$$\text{COPxVelSD} \;=\; \sqrt{\frac{\sum (COPxVel \;-\; CO\bar{P}xVel)^2}{n \;-\; 1}} \;=\; \sqrt{C}$$

$$\delta \text{COPxVelSD} \; \leq \; \frac{1}{2} \; * \; \delta C \quad \leq \; \frac{1}{2} \; * 124.741 \qquad \boldsymbol{\leq \; 62.370 \text{ mm/s}}$$

For n = 640 (5s)

Let A = $(COPxVel \;-\; CO\bar{P}xVel)^2$

$\delta A \quad \leq 2 * (COPxVel \;-\; CO\bar{P}xVel)$

where $\qquad \delta COPxVel \qquad\qquad \leq$ 31.104 mm/s

and, using the process outlined in the averages paragraph above

maximum $CO\bar{P}xVel$ (simply the error of a single measure)

$\leq$ 31.104 mm/s

$\delta A \quad \leq \; 2 \; * \; (\; 31.104 \; + \; 31.104) \quad \leq \; 124.416$

$\text{Let B} \;=\; \sum (COPxVel \;-\; CO\bar{P}xVel)^2 \;=\; \sum (\text{A})$

$\delta B \quad \leq \sum \delta A \qquad \leq 124.496 \; * \; 640 \qquad \leq 79626.240$

$$\text{Let C} \;=\; \frac{\sum (COPxVel \;-\; CO\bar{P}xVel)^2}{n \;-\; 1} \;=\; \frac{B}{n-1}$$

$$\delta C \quad \leq \delta B \; * \; \frac{1}{n-1} \qquad \leq \; 79626.240 \; * \; \frac{1}{640 \;-\; 1} \quad \leq \; 124.611$$

$$\text{COPxVelSD} = \sqrt{\frac{\sum (COPxVel - CO\bar{P}xVel)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPxVelSD} \le \frac{1}{2} * \delta\text{C} \le \frac{1}{2} * 124.611 \qquad \le \mathbf{62.305\ mm/s}$$

COPyVelSD

The standard deviation of COPyVel is calculated by:

$$\text{COPyVelSD} = \sqrt{\frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1}}$$

Where $COPyVel$ = value of COPY velocity for 1 to n samples

$CO\bar{P}yVel$ = mean of n COPY velocity values

n = number of samples

Approximate error due to quantisation will be

For n = 128 (1s)

Let A = $(COPyVel - CO\bar{P}yVel)^2$

δA = 2 * $(\delta COPyVel + \delta CO\bar{P}yVel)$

where $\delta COPyVel$ = 23.808 mm/s

and, using the process outlined in the averages paragraph above

approximate $CO\bar{P}yVel$ 1s $= \frac{\sqrt{23.808^2 * 128}}{128}$ = 2.104 mm/s

δA = 2 * (23.808 + 2.104) = 51.825

Let B = $\sum (COPyVel - CO\bar{P}yVel)^2 = \sum (A)$

$\delta B = \sum \delta A = \sqrt{51.825^2 * 128}$ (using quadrature) = 586.330

$$\text{Let C} = \frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n-1} = \frac{B}{n-1}$$

$$\delta C = \delta B * \frac{1}{n-1} = 586.330 * \frac{1}{128-1} = 4.617$$

$$\text{COPyVelSD} = \sqrt{\frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n-1}} = \sqrt{C}$$

$$\delta\text{COPyVelSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 4.617 \quad = \mathbf{2.308\ mm/s}$$

For n = 384 (3s)

Let A = $(COPyVel - CO\bar{P}yVel)^2$

$\delta A = 2 * (\delta COPyVel + \delta CO\bar{P}yVel)$

where $\delta COPyVel$ = 23.808 mm/s

and, using the process outlined in the averages paragraph above

approximate $CO\bar{P}yVel$ 1s $= \frac{\sqrt{23.808^2 * 384}}{384}$ = 1.215 mm/s

$\delta A = 2 * (23.808 + 1.215) = 50.046$

Let B = $\sum (COPyVel - CO\bar{P}yVel)^2 = \sum$ (A)

$\delta B = \sum \delta A = \sqrt{50.046^2 * 384}$ (using quadrature) = 980.695

$$\text{Let C} = \frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n-1} = \frac{B}{n-1}$$

$$\delta C = \delta B * \frac{1}{n-1} = 980.695 * \frac{1}{384-1} = 2.561$$

$$\text{COPyVelSD} = \sqrt{\frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPyVelSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 2.561 \qquad = \mathbf{1.280\ mm/s}$$

For n = 640 (5s)

Let A = $(COPyVel - CO\bar{P}yVel)^2$

$$\delta A = 2 * (\delta COPyVel + \delta CO\bar{P}yVel)$$

where $\delta COPyVel$ = 23.808 mm/s

and, using the process outlined in the averages paragraph above

approximate $CO\bar{P}yVel$ 5s $= \dfrac{\sqrt{23.808^2 * 640}}{640}$ = 0.941 mm/s

$$\delta A = 2 * (23.808 + 0.941) = 49.498$$

Let B $= \sum (COPyVel - CO\bar{P}yVel)^2 = \sum (A)$

$$\delta B = \sum\delta A = \sqrt{49.498^2 * 640} \text{ (using quadrature)} = 1252.216$$

$$\text{Let } C = \frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta C = \delta B * \frac{1}{n-1} = 1252.216 * \frac{1}{640 - 1} = 1.960$$

$$\text{COPyVelSD} = \sqrt{\frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPyVelSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 1.960 \qquad = \mathbf{0.980\ mm/s}$$

And will be no more than

For n = 128 (1s)

Let A = $(COPyVel - CO\bar{P}yVel)^2$

δA $\leq 2 * (\delta COPyVel + \delta CO\bar{P}yVel)$

where $\delta COPyVel$ $\leq$ 34.560 mm/s

and, using the process outlined in the averages paragraph above

maximum $CO\bar{P}yVel$ (simply the error of a single measure)

$\leq$ 34.560 mm/s

δA $\leq 2 * (34.560 + 34.560) \leq 138.240$

Let B $= \sum (COPyVel - CO\bar{P}yVel)^2 = \sum (A)$

δB $\leq \sum \delta A \leq 138.240 * 128 \leq 17694.720$

Let C $= \dfrac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1} = \dfrac{B}{n-1}$

δC $\leq \delta B * \dfrac{1}{n-1} \leq 17694.720 * \dfrac{1}{128-1} \leq 139.329$

COPyVelSD $= \sqrt{\dfrac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1}} = \sqrt{C}$

δCOPyVelSD $\leq \dfrac{1}{2} * \delta C \leq \dfrac{1}{2} * 139.329$ **$\leq$ 69.664 mm/s**

For n = 384 (3s)

Let A = $(COPyVel - CO\bar{P}yVel)^2$

δA $\leq 2 * (\delta COPyVel + \delta CO\bar{P}yVel)$

where $\delta COPyVel$ $\leq$ 34.560 mm/s

and, using the process outlined in the averages paragraph above

maximum $CO\bar{P}YVel$ (simply the error of a single measure)

$\leq$ 34.560 mm/s

$\delta A \quad \leq 2 * (34.560 + 34.560) \leq 138.240$

Let B $= \sum (COPyVel - CO\bar{P}yVel)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 138.240 * 384 \quad \leq 53084.160$

$$\text{Let C} = \frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1} = \frac{B}{n-1}$$

$$\delta C \leq \delta B * \frac{1}{n-1} \leq 53084.160 * \frac{1}{384 - 1} \leq 138.601$$

$$\text{COPyVelSD} = \sqrt{\frac{\sum (COPyVel - CO\bar{P}yVel)^2}{n - 1}} = \sqrt{C}$$

$$\delta\text{COPyVelSD} \leq \frac{1}{2} * \delta C \leq \frac{1}{2} * 138.601 \quad \mathbf{\leq 69.300\ mm/s}$$

For n = 640 (5s)

Let A = $(COPyVel - CO\bar{P}yVel)^2$

$\delta A \quad \leq 2 * (\delta COPyVel + \delta CO\bar{P}yVel)$

where $\delta COPyVel$ $\leq$ 34.560 mm/s

and, using the process outlined in the averages paragraph above

maximum $CO\bar{P}yVel$ (simply the error of a single measure)

$\leq$ 34.560 mm/s

$\delta A \quad \leq 2 * (34.560 + 34.560) \leq 138.240$

Let B $= \sum (COPyVel - CO\bar{P}yVel)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 138.240 * 640 \quad \leq 88473.600$

Let C $= \dfrac{\sum (COPyVel - \overline{COPyVel})^2}{n - 1} = \dfrac{B}{n-1}$

$\delta C \leq \delta B * \dfrac{1}{n-1} \leq 88473.600 * \dfrac{1}{640 - 1} \leq 138.456$

COPyVelSD $= \sqrt{\dfrac{\sum (COPyVel - \overline{COPyVel})^2}{n - 1}} = \sqrt{C}$

δCOPyVelSD $\leq \dfrac{1}{2} * \delta C \leq \dfrac{1}{2} * 138.456$ **$\leq$ 629.228 mm/s**

COPAbsSpeedAve

COPAbsSpeedAve is calculated by

COPAbsSpeedAve =

$$\frac{(COPAbsSpeed_1 + COPAbsSpeed_2 + \ldots + COPAbsSpeed)}{n}$$

Where $COPAbsSpeed_{1,2\ldots n}$ = COPAbs Speed values at n = 1,2..n

n = number of samples

δCOPAbs Speed Ave =

$$\frac{(\delta COPAbsSpeed_1 + \delta COPAbsSpeed_2 + \ldots + \delta COPAbsSpeed_n)}{n}$$

Where $\delta COPAbsSpeed_{1,2\ldots n}$ = COPAbs Speed error for a single measure

(calculated above)

= 45.824mm/s

$\leq$ 65.614 mm/s

Approximate error due to quantisation will be:

At n = 128 (1s)

δCOPAbs Speed Ave = (using quadrature)

$$\frac{\sqrt{\delta COPAbsSpeed_1{}^2 + \delta COPAbsSpeed_2{}^2 + \ldots + \delta COPAbsSpeed_{128}{}^2}}{128}$$

$$= \frac{\sqrt{45.824_1{}^2 + 45.824_2{}^2 + \ldots + 45.824_{128}{}^2}}{128}$$

= **4.050 mm/s**

At n = 384 (3s)

δCOPAbs Speed Ave = (using quadrature)

$$\frac{\sqrt{\delta COPAbsSpeed_1{}^2 + \delta COPAbsSpeed_2{}^2 + \ldots + \delta COPAbsSpeed_{384}{}^2}}{384}$$

$$= \frac{\sqrt{45.824_1{}^2 + 45.824_2{}^2 + \ldots + 45.824_{384}{}^2}}{384}$$

= **2.338 mm/s**

At n = 640 (5s)

δCOPAbs Speed Ave = (using quadrature)

$$\frac{\sqrt{\delta COPAbsSpeed_1{}^2 + \delta COPAbsSpeed_2{}^2 + \ldots + \delta COPAbsSpeed_{640}{}^2}}{640}$$

$$= \frac{\sqrt{45.824_1{}^2 + 45.824_2{}^2 + \ldots + 45.824_{640}{}^2}}{640}$$

= **1.811 mm/s**

And, in all measurement periods, will be no more than

$$\leq$$

$$\frac{(\delta COPAbsSpeed_1 + \delta COPAbsSpeed_2 + \ldots + \delta COPAbsSpeed_n)}{n}$$

$$\leq \frac{(65.614 + 65.614 + \ldots + 65.614_n)}{n}$$

≤ **65.614mm/s**

(As the maximum error is effectively (n * maximum error for a single value)/n, n cancels out and the maximum error is independent of the number of samples)

COPAbsSpeedSD

The standard deviation of COPAbsSpeed is calculated by:

$$\text{COPAbsSpeedSD} = \sqrt{\frac{\sum(COPABSpeed - COPA\bar{B}Sspeed)^2}{n-1}}$$

Where $COPABSspeed$ = value of COPABS speed for n samples

$COPA\bar{B}Sspeed$ = mean of n COPABS speed values

n = number of samples

Approximate error due to quantisation will be

For n = 128 (1s)

Let A = $(COPABSspeed - COPA\bar{B}Sspeed)^2$

$$\delta A = 2 * (\delta COPABSspeed + \delta COPA\bar{B}Sspeed)$$

where $\delta COPABSspeed$ = 45.824 mm/s

and, using the process outlined in the averages paragraph above

approximate $COPA\bar{B}Sspeed$ 1s $= \frac{\sqrt{45.824^2 * 128}}{128}$ = 4.050 mm/s

$$\delta A = 2 * (45.824 + 4.050) = 99.749$$

Let B = $\sum(COPABSspeed - COPA\bar{B}Sspeed)^2 = \sum(A)$

$\delta B = \sum\delta A = \sqrt{99.749^2 * 128}$ (using quadrature) = 1128.527

Let C $= \dfrac{\sum(COPABSspeed - COP\overline{ABS}speed)^2}{n-1} = \dfrac{B}{n-1}$

$\delta C \quad = \delta B \ * \ \dfrac{1}{n-1} \quad = \ 1128.527 \ * \ \dfrac{1}{128-1} \quad = \ 8.886$

COPAbsSpeedSD $= \sqrt{\dfrac{\sum(COPABSspeed - COP\overline{ABS}speed)^2}{n-1}} = \sqrt{C}$

δCOPAbsSpeedSD $= \dfrac{1}{2} \ * \ \delta C \quad = \dfrac{1}{2} * 8.886$ **= 4.443 mm/s**

For n = 384 (3s)

Let A = $(COPABSspeed - COP\overline{ABS}speed)^2$

$\delta A \quad = 2 * \ (\delta COPABSspeed \ + \ \delta COP\overline{ABS}speed)$

where $\delta COPABSspeed$ = 45.824 mm/s

and, using the process outlined in the averages paragraph above

approximate $COP\overline{ABS}speed$ 1s $= \dfrac{\sqrt{45.824^2 * 384}}{384} = 2.338$ mm/s

$\delta A \quad = \ 2 \ * \ (45.824 \ + \ 2.338) \quad = \ 96.325$

Let B $= \sum(COPABSspeed - COP\overline{ABS}speed)^2 = \sum$ (A)

$\delta B \quad = \sum\delta A \quad = \sqrt{96.325^2 * 384}$ (using quadrature) = 1887.575

Let C $= \dfrac{\sum(COPABSspeed - COP\overline{ABS}speed)^2}{n-1} = \dfrac{B}{n-1}$

$\delta C \quad = \delta B \ * \ \dfrac{1}{n-1} \quad = \ 1887.575 \ * \ \dfrac{1}{384 - 1} \quad = \ 4.928$

COPAbsSpeedSD $= \sqrt{\dfrac{\sum(COPABSspeed - COP\overline{ABS}speed)^2}{n-1}} = \sqrt{C}$

$$\delta \text{COPAbsSpeedSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 4.928 = \mathbf{2.464\ mm/s}$$

For n = 640 (5s)

Let A = $(COPABSspeed - COPA\bar{B}Sspeed)^2$

$$\delta A = 2 * (\delta COPABSspeed + \delta COPA\bar{B}Sspeed)$$

where $\delta COPABSspeed$ = 45.824 mm/s

and, using the process outlined in the averages paragraph above

$$\text{approximate } COPA\bar{B}Sspeed \text{ 1s} = \frac{\sqrt{45.824^2 * 640}}{640} = 1.811 \text{ mm/s}$$

$$\delta A = 2 * (45.824 + 1.811) = 95.271$$

Let B $= \sum (COPABSspeed - COPA\bar{B}Sspeed)^2 = \sum (A)$

$$\delta B = \sum \delta A = \sqrt{95.271^2 * 640} \text{ (using quadrature)} = 2410.179$$

Let C $= \dfrac{\sum (COPABSspeed - COPA\bar{B}Sspeed)^2}{n-1} = \dfrac{B}{n-1}$

$$\delta C = \delta B * \frac{1}{n-1} = 2410.179 * \frac{1}{640 - 1} = 3.772$$

$$\text{COPAbsSpeedSD} = \sqrt{\frac{\sum (COPABSspeed - COPA\bar{B}Sspeed)^2}{n-1}} = \sqrt{C}$$

$$\delta \text{COPAbsSpeedSD} = \frac{1}{2} * \delta C = \frac{1}{2} * 3.772 = \mathbf{1.886\ mm/s}$$

And will be no more than

For n = 128 (1s)

Let A = $(COPABSspeed - COPA\bar{B}Sspeed)^2$

δA $\leq 2 * (\delta COPABSspeed + \delta COPA\overline{B}Sspeed)$

where $\delta COPABSspeed$ $\leq$ 65.614 mm/s

and, using the process outlined in the averages paragraph above

maximum $COPA\overline{B}Sspeed$ (simply the error of a single measure)

$\leq$ 65.614 mm/s

δA $\leq$ 2 * (65.614 + 65.614) $\leq$ 262.456

Let B $= \sum(COPABSspeed - COPA\overline{B}Sspeed)^2 = \sum$ (A)

δB $\leq \sum\delta$A $\leq$ 262.456 * 128 $\leq$ 33594.368

Let C $= \dfrac{\sum(COPABSspeed - COPA\overline{B}Sspeed)^2}{n-1} = \dfrac{B}{n-1}$

δC $\leq \delta B * \dfrac{1}{n-1}$ $\leq 33594.368 * \dfrac{1}{128-1}$ $\leq$ 264.523

COPAbsSpeedSD $= \sqrt{\dfrac{\sum(COPABSspeed - COPA\overline{B}Sspeed)^2}{n-1}} = \sqrt{C}$

δCOPAbsSpeedSD $\leq \dfrac{1}{2} * \delta C$ $\leq \dfrac{1}{2} * 264.523$ **≤ 132.261 mm/s**

For n = 384 (3s)

Let A = $(COPABSspeed - COPA\overline{B}Sspeed)^2$

δA $\leq 2 * (\delta COPABSspeed + \delta COPA\overline{B}Sspeed)$

where $\delta COPABSspeed$ $\leq$ 65.614 mm/s

and, using the process outlined in the averages paragraph above

maximum $COPA\overline{B}Sspeed$ (simply the error of a single measure)

$\leq$ 65.614 mm/s

$\delta A \quad \leq 2 * (65.614 + 65.614) \leq 262.456$

Let B $= \sum (COPABSspeed - COPA\overline{B}Sspeed)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 262.456 * 384 \quad \leq 100783.104$

Let C $= \dfrac{\sum (COPABSspeed - COPA\overline{B}Sspeed)^2}{n-1} = \dfrac{B}{n-1}$

$\delta C \quad \leq \delta B * \dfrac{1}{n-1} \quad \leq 100783.104 * \dfrac{1}{384 - 1} \leq 263.141$

COPAbsSpeedSD $= \sqrt{\dfrac{\sum (COPABSspeed - COPA\overline{B}Sspeed)^2}{n-1}} = \sqrt{C}$

δCOPAbsSpeedSD $\leq \dfrac{1}{2} * \delta C \quad \leq \dfrac{1}{2} * 263.141$ **≤ 131.571 mm/s**

For n = 640 (5s)

Let A = $(COPABSspeed - COPA\overline{B}Sspeed)^2$

$\delta A \quad \leq 2 * (\delta COPABSspeed + \delta COPA\overline{B}Sspeed)$

where $\delta COPABSspeed$ ≤ 65.614 mm/s

and, using the process outlined in the averages paragraph above

maximum $COPA\overline{B}Sspeed$ (simply the error of a single measure)

≤ 65.614 mm/s

$\delta A \quad \leq 2 * (65.614 + 65.614) \leq 262.456$

Let B $= \sum (COPABSspeed - COPA\overline{B}Sspeed)^2 = \sum (A)$

$\delta B \quad \leq \sum \delta A \quad \leq 262.456 * 640 \quad \leq 167971.840$

Let C $= \dfrac{\sum (COPABSspeed - COPA\overline{B}Sspeed)^2}{n-1} = \dfrac{B}{n-1}$

$$\delta C \leq \delta B * \frac{1}{n-1} \qquad \leq 167971.840 * \frac{1}{640 - 1} \leq 262.867$$

$$\text{COPAbsSpeedSD} \quad = \sqrt{\frac{\sum(COPABSspeed - COPA\bar{B}Sspeed)^2}{n-1}} = \sqrt{C}$$

$$\delta \text{COPAbsSpeedSD} \leq \frac{1}{2} * \delta C \qquad \leq \frac{1}{2} * 262.867 \qquad \mathbf{\leq 131.433\ mm/s}$$

Tz

Tz is calculated using the following formula

$$Tz = Mz + (Fx * COPy) - (Fy * COPx)$$

The error for a single measure of Tz is

(measurement step for Mz = 0.15 Nm or δMz = +/- 0.075 Nm)

$$\delta Tz \leq \delta Mz + (\delta Fx + \delta COPy) + (\delta Fy + \delta COPx)$$

$$\leq 0.075 + (0.185 + 0.3) + (0.185 + 0.2)$$

$$\leq 0.945\ \text{Nm}$$

TzRange:

TzRange = Tz (maximum) - Tz (minimum)

$$\delta Tz = \sqrt{(\delta Tz(\max))^2 + (\delta Tz(\min))^2}$$

$$= \sqrt{0.945^2 + 0.945^2} \qquad \mathbf{= 1.336\ Nm}$$

and will be no more than

$$\delta Tz \leq \delta Tz\max + \delta Tz\min \qquad \leq 0.945 + 0.945 \qquad \mathbf{\leq 1.890\ Nm}$$

Minimum measurement steps

Fx, Fy

Fx and Fy are measured directly by the force plate and given in table 5.1.1.1 (repeated here for clarity). **= 0.37N**

COPx and COPy displacement

COPx and COPy displacement measurement steps for a 750N subject were calculated previously and reported in table 5.1.7 (repeated here for clarity).

COPx **= 0.320mm**

COPy **= 0.453mm**

COPxVel

COPxVel (measurement step) $= \dfrac{COPx(measurement.step)}{2h}$

where

COPx (measurement step) = 0.32 mm (from table 5.1.7)

COPxVel (measurement step) $= \dfrac{0.320}{0.0156}$ **= 20.513 mm/s**

The same value will exist for COPxSpeed **= 20.513 mm/s**

COPyVel

COPyVel (measurement step) $= \dfrac{COPy(measurement.\,step)}{2h}$

where

COPy (measurement step) = the measurement step of COPy

= 0.453 mm (from table 5.1.7)

COPyVel (measurement step) $= \dfrac{0.453}{0.0156}$ **= 29.038 mm/s**

The same value will exist for COPySpeed **= 29.038 mm/s**

COPAbsSpeed

There are a number of possibilities in examining the measurement step for COPAbs values. The minimum measurement step for speed will exist where movement only occurred in COPx direction (ie. COPySpeed equals zero). As such, the measurement step would be the same as for COPxSpeed, 20.513mm/s.

Where movement occurs in both directions, the measurement step will be:

COPAbsSpeed (measurement step)

$$= \sqrt{(vel(COPX(measurement.step))^2 + (vel(COPY(measurement.step))^2}$$

$$= \sqrt{(20.513)^2 + (29.038)^2}$$ **= 35.553 mm/s**

The same value will exist for COPAbsVel **= 35.553 mm/s**

APPENDIX C

Data for body sway, aim point and shooting performance parameters for all shooters

Not available

APPENDIX D

Assessment of smoothing for experimental data

D.1 Analysis of signal in individual force plate channels

Fx

The spectral analyses of the Fx channel for individual trials showed the majority of activity existed below 2Hz (figure D.1). This was interpreted as being produced by body sway, as it exists within the ranges of 0Hz to 3Hz reported by other authors as being associated with sway signal (eg. Scott and Dzendolet, 1992; Liu and Lawson, 1995; Soames and Atha, 1982). A 4Hz peak was also prominent in this data, as can be noted in figure D.1. Goldie (1985) also reports finding a 4Hz peak in force channels during two-footed quiet stance, attributing this peak to the ballistocardiogram (BCG). This was interpreted as the BCG in this study also and did not represent body sway signal. Some activity was evident in the frequencies above 4Hz, with small amplitude peaks at a number of frequencies. These were interpreted by this researcher as being generated by noise in the system and signal produced by the shooter that was not associated with sway.

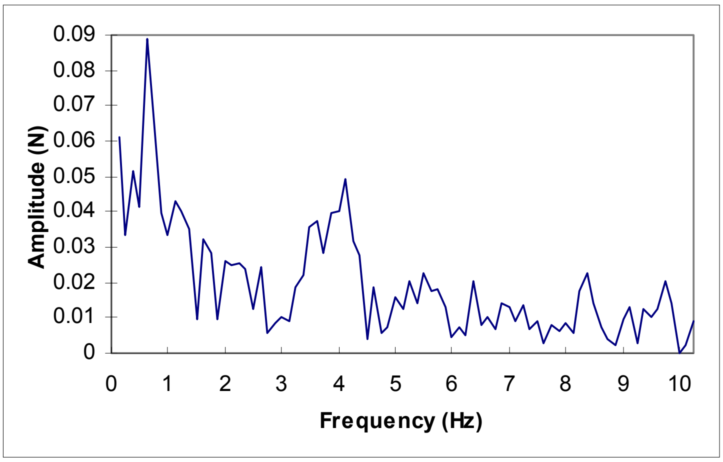

Figure D.1: Amplitude spectrum of Fx raw data calculated from a single rifle-shooting trial over 5s.

Figure D.2 shows the ensemble averaged spectral data for Fx. Most activity is still contained below 2Hz, although there is a peak at 2.75Hz. This peak is still within the ranges reported by other authors (0-3Hz) as being associated with body sway, mentioned previously. As such, this signal was interpreted as body sway signal. Evident also is the 4Hz spike, attributed to the BCG. Another peak at approximately 5.5Hz was produced from the ensemble average. This peak was only slightly evident in the single trial presented in figure D.1. This 5.5Hz peak lies within the 5Hz to 10Hz band reported by Thomas and Whitney (1959) as being generated by muscle tremor. This may be the source of this peak in the data. Regardless, it was considered, due to the higher frequency of the movement, that it did not relate to body sway in terms of CG movement.

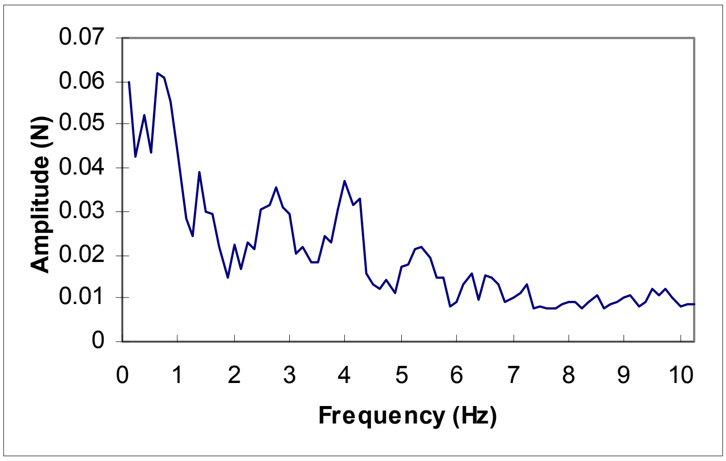

Figure D.2: Ensemble averaged spectrum of Fx raw data calculated from ten shooting trials over 5s.

Figure D.3 shows the residual for Fx smoothed at cut-off frequencies of 2Hz to 10Hz for the rifle-shooting trial. Examining the curve from right to left, the Fx residual shows a fairly consistent increase from 8Hz to 2Hz, with a slightly greater increase from 3Hz. As 2Hz was the lowest cut-off frequency used, any activity that occurs below this level will not be evident in this curve.

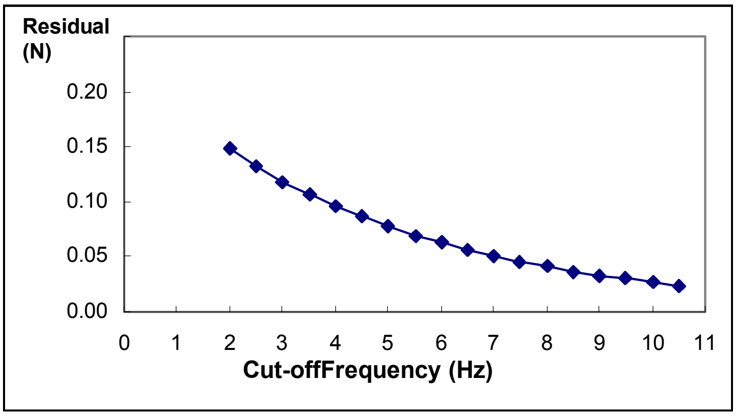

Figure D.3: Residual analysis of Fx using a range of cut-off frequencies from 2Hz to 10.5Hz.

It is worth noting here that the use of the residual curve as the basis for choosing a smoothing cut-off frequency was somewhat limited. The curve in figure D.3 is gradual, with no point of rapid increase. Winter (1990) describes this point as being associated with the point at which the smoothing begins to eliminate true signal, rather than noise. Winter also describes a useful method for choosing a cut-off frequency for smoothing which involves projecting a line along this curve to intersect with the Y-axis (line ‘a’ in figure D.4). A line is then projected horizontally from this point to the residual curve (line b) and then vertically to the X-axis (line c). The point of intersection with the X-axis will correspond to the cut-off frequency used for equal amounts of noise reduction and signal distortion. Unfortunately, this point does not exist in all curves analysed as the data in this study contains signal that is not noise, but is not associated with body sway either; namely the activity between 4Hz and 7Hz from BCG and possibly muscle tremor. As this activity is not associated with CG movement, it needs to be eliminated from the data. While some curves showed a clearer distinction between sway signal and noise (eg. figure D.7), the residual analysis alone did not provide enough information for the choice of cut-off frequency for smoothing, and was used in conjunction with the spectral analysis to decide on a cut-off frequency.

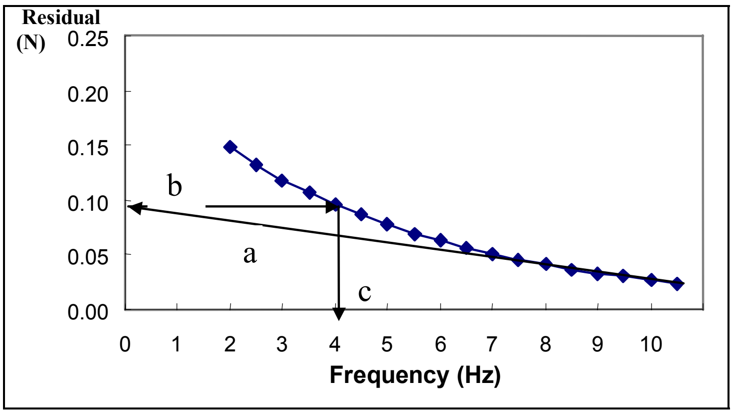

Figure D.4: Example of use of the residual curve for deciding upon a cut-off frequency.

Fy

Fy channel spectral analysis showed a smaller maximum peak but greater amplitude in slightly higher frequencies than Fx. A band of activity exists below 1.5Hz, with another band of activity between 2.5Hz and 4Hz with numerous peaks about the 2.75Hz and 4Hz frequency (figure D.5). There was a slight drop in amplitude between these frequencies, which possibly represents the point at which the signal due to body sway ceased and the signal due to the BCG began. The 5.5Hz peak found in Fx is also present in the Fy signal, although it was relatively small for this trial.

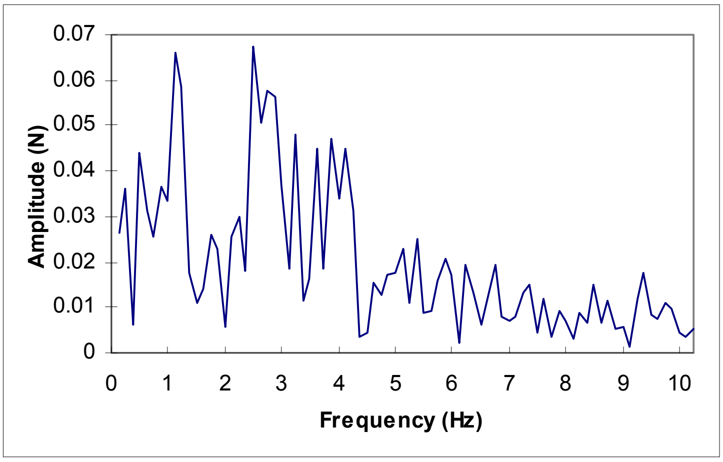

Figure D.5: Amplitude spectrum of Fy raw data calculated from a single rifle-shooting trial over 5s.

Figure D.6 shows the ensemble averaged spectral data for Fy. Most activity is contained below 3Hz-4Hz. The activity at 2.75Hz is consistent across trials, as indicated by the presence of the peak in the ensemble averaged frequency spectrum. There is slightly less amplitude generally and slightly more activity in frequencies around 3Hz in the Fy signal compared to the Fx channel, indicating a slightly higher frequency of movement in this channel and axis. This slightly higher frequency of movement was also evident in the group based body sway data for rifle shooters (section 5.2.2 and 5.2.3). The activity at 4Hz is also quite strong. The 5.5Hz signal is not as noticeable as in the spectral analysis of Fx (figure D.1), although the amplitudes are similar. Fy has more activity across the 4Hz to 5.5Hz band and so peaks are not as evident.

Figure D.6: Ensemble averaged spectrum of Fy raw data calculated from ten shooting trials over 5s.

Examining the Fy residual graph (figure D.7) from right to left, a gradual increase between 10.5Hz to approximately 6Hz can be noticed, with a more rapid increase beginning around 4Hz. This was interpreted as indicating the majority of sway signal lay below 4Hz, with noise existing in the higher frequencies. As was the case with the Fx curve, there was still influence from the 4Hz and 5.5Hz frequencies in the signal, but these were relatively smaller. As such a clearer distinction between signal and noise is made by this curve, with a trade off between signal and noise being approximately 4Hz.

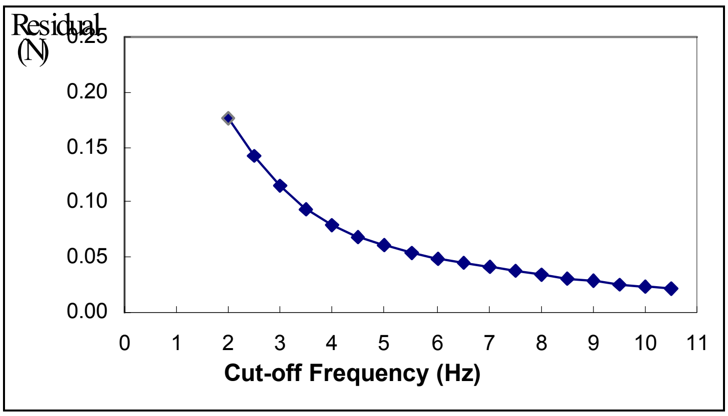

Figure D.7: Residual analysis of Fy using a range of cut-off frequencies from 2Hz to 10.5Hz.

Fz

Fz showed a considerably different amplitude spectrum to that of all other channels (figure D.8). As movement in quiet standing will have minimal vertical component, only very low levels of activity might be expected below 3Hz which is evident from the spectral analysis. In between 3Hz and 7Hz, frequencies of reasonably large magnitude existed, with a 4Hz and a 5.5Hz peak consistently evident. The magnitudes of these peaks were considerably larger than the peaks at these frequencies in Fx and Fy. As there is virtually no vertical movement of the body, as mentioned, during shooting, these frequencies might be expected to be more prominent in the Fz curve, although the amplitude of the peaks is surprising.

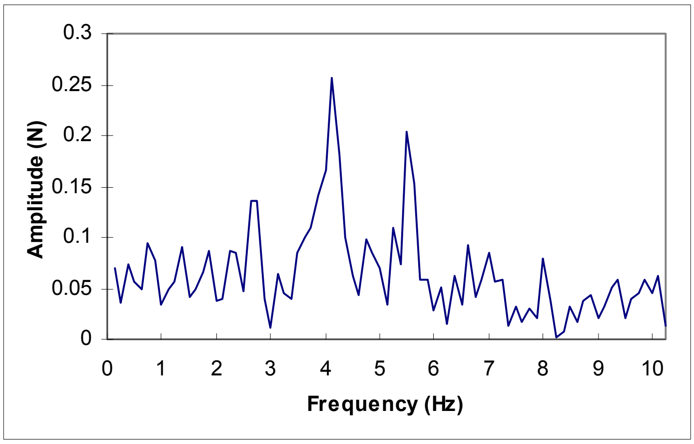

Figure D.8: Amplitude spectrum of Fz raw data calculated from a single rifle-shooting trial over 5s.

This very different nature of Fz warrants further discussion. As can be noted from the raw Fz data curve presented in figure D.9, some high frequencies (greater than approximately 5Hz) of small magnitude exist in the signal, which gives the curve the slightly 'rough' look. This was thought to be generated by noise in the system and possibly muscle tremor. A low level (approximately 0.2Hz) signal is also present, evident in the slight rise and fall of the approximate average of the signal across the 5s. This was also evident in trials with a 750N weight and with an unloaded force plate. As such, this signal would seem to be noise, or a combination of sway and noise in Fz. This noise could not be removed from the signal and remained a limitation of the measurement. Noticeable also is a number of large spikes (seven in all) in the negative direction at fairly regular intervals in the data. This was interpreted as the BCG signal, also found by Goldie (1985) in Fz channel data. This BCG signal at 4Hz poses a difficulty in smoothing, as it is not associated with sway but is present at a frequency that is close to body sway frequencies. Further, the amplitude contained in this signal is large relative to the curve itself and to other channels, which will increase its influence in calculations.

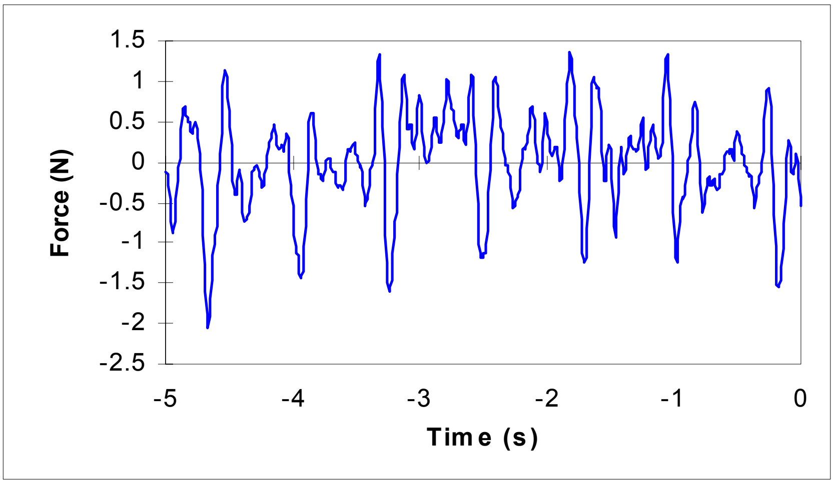

Figure D.9: Fz raw data curve showing the effects of the BCG.

Figure D.10 shows the ensemble average of the spectral analyses of Fz for ten trials. Strongly evident are the 4Hz and 5.5Hz signals. There is also a peak at 7Hz. The origins of this signal are unclear and beyond the scope of this study, but it lies in the frequency band of 5Hz to 10Hz reported by Thomas and Whitney (1959) as being associated with muscle tremor and may be associated with this factor, as well as the

5.5Hz signal. Regardless, the 7Hz signal was considered to be too high to be associated with CG movement. Some activity exists in the very low frequencies below 1Hz, which is probably the low amount of sway activity that will be picked up in Fz. It could also be due to vertical movement of the gun or body position during the aiming process. There is also a strong 2.75Hz signal in this spectral analysis, as was evident in Fx and Fy channels. This was considered to be associated with body sway signal.

Figure D.10: Ensemble averaged spectrum of Fz raw data from ten shooting trials over 5s.

The Fz residual graph (figure D.11) showed considerably larger residual values than other channels. This is due to the higher frequency activity existing in this channel and the larger amplitudes of signal which were largely due to the BCG, as was noted in the spectral analysis presented in figure D.10. Due to the relatively large amplitude between 4Hz and 8Hz, the difference between the raw and smoothed value will be large in this band, as the smoothing reduces or eliminates the signal at these major frequencies. This residual analysis provided no indications of an appropriate cut-off frequency.

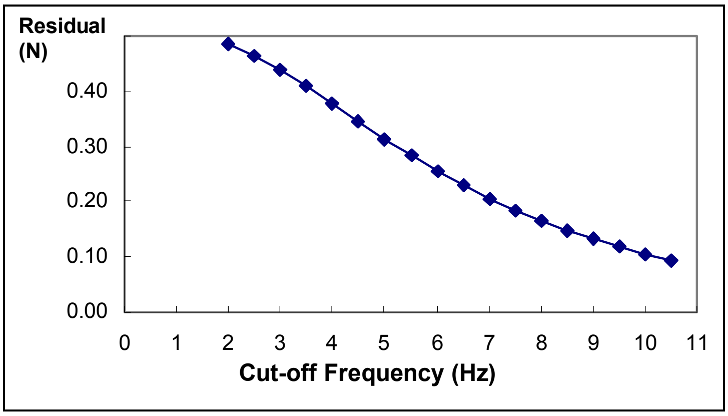

Figure D.11: Residual analysis of Fz using a range of cut-off frequencies from 2Hz to 10.5Hz.

The large amplitude of the 4Hz peak in Fz poses a difficulty in deciding on a cut-off frequency for smoothing for this channel. Fz is a major contributor in COP calculations. The effects of the BCG in Fz will influence COP calculations if not eliminated. Some canceling of the BCG will occur in the COP calculation, as Fz is present in both the numerator and denominator of the COP equation. Recalling that COP equals the moment about an axis (and the horizontal force) divided by Fz and that the moment is Fz multiplied by the distance of the line of action from the centre of the plate. However, as the AMTI LG6-4 is 1200mm by 600mm, the maximum possible moment will be 0.6 times Fz in the Y-axis and 0.3 times Fz in the X-axis. Spectral analyses of the COP traces indicated the majority of activity occurred below 2.5Hz, with only relatively low amplitude 4Hz peaks (figures D.21 to D.24), indicating that there is a degree of, but not complete, canceling of the BCG in the COP calculation. This has implications for smoothing. The 4Hz signal generated by the BCG needs to be removed, as it is not produced by body sway, while not removing the body sway signal that exists below 3Hz. This is one of the major decision points upon which the choice of cut-off was based and is summarised in section D.4.

Mx

Mx showed most activity below 2Hz, with a band of activity around 2.75Hz (figure D.12). These frequency peaks were interpreted as being generated by body sway. There is some indication of the 4Hz activity in this channel, although it is reduced in both absolute and relative terms compared with the 4Hz peak in Fz. There is no evidence of the 5.5Hz peak in the Mx signal.

Figure D.12: Amplitude spectrum of Mx raw data calculated from a single rifle-shooting trial over 5s.

The ensemble averaged spectral analysis for Mx (figure D.13) shows the major activity and two large peaks existed below 2Hz, with the 2.75Hz peak remaining prevalent across trials also. There is only a small amount of activity at 4Hz, which tends to overlap with the lower frequencies. A steady decrease in the amplitude in frequencies from 3Hz to 10Hz is evident. This was considered to be a combination of BCG, muscle tremor and noise.

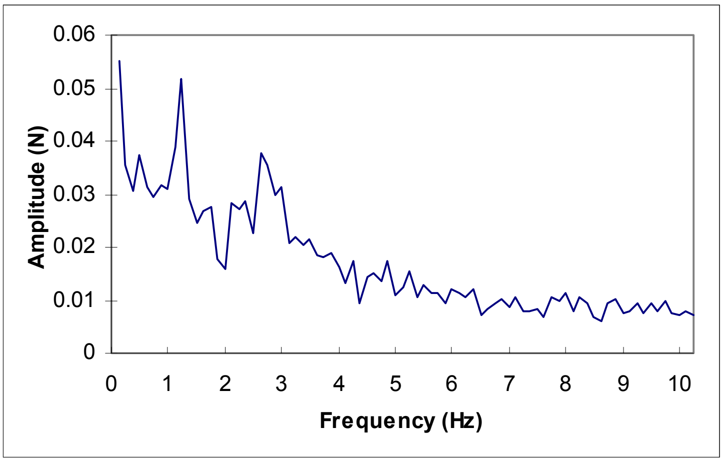

Figure D.13: Ensemble averaged spectrum of Mx raw data calculated from ten shooting trials over 5s.

Figure D.14 shows the residual for Mx across the smoothing cut-off frequencies used. Examining the curve from right to left, there is a fairly linear increase in the residual from 10.5Hz to 4Hz preceding a marked increase between 4Hz and 2Hz. This was interpreted as indicating the majority of signal existed below 4Hz, with mostly noise existing above this level.

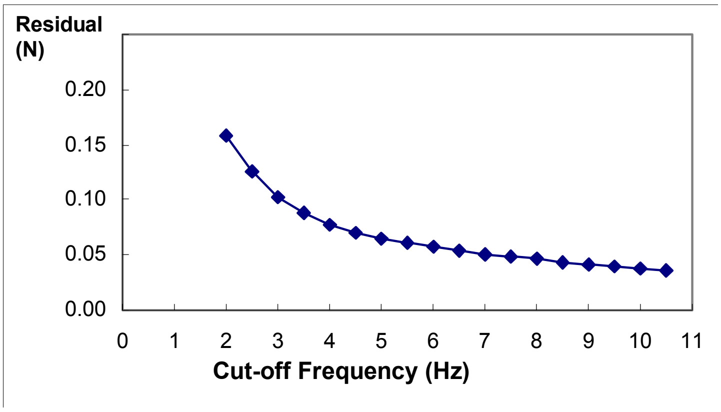

Figure D.14: Residual analysis of Mx using a range of cut-off frequencies from 2Hz to 10.5Hz.

My

Almost all of the activity in My lay below 1.5Hz. As can be noted in figure D.15, the amplitude of this frequency was high, particularly compared to the other channels, indicating a large amount of signal in this channel. This was interpreted as large amounts of body sway signal in this channel, which were considerably greater than the signal evident in Mx (figure D.13). As can be noted in section D.2, COPx showed more activity and movement compared with COPy. This is consistent with these results, as My is the major contributor to COPx, while Mx is the major contributor to COPy. 4Hz and 5.5Hz peaks were evident in the data, although at a very small relative amplitude compared with the peak amplitudes in the signal.

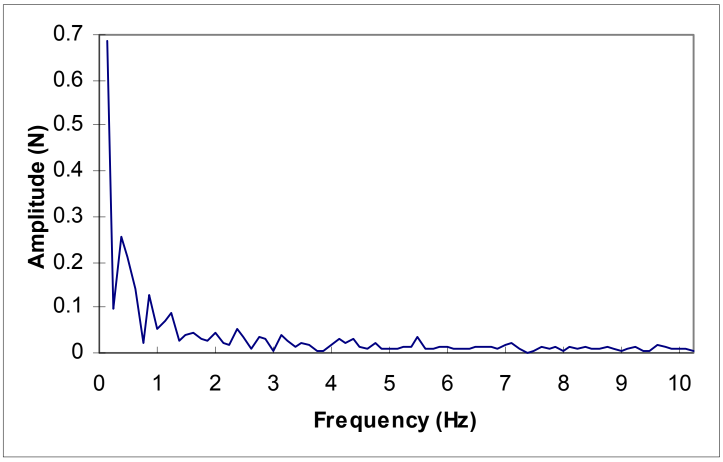

Figure D.15: Amplitude spectrum of My raw data calculated from a single rifle-shooting trial over 5s.

The ensemble averaged spectral analysis for My (figure D.16) shows the major activity exists below 2Hz, with the amplitude of this activity remaining quite high relative to other frequencies and other channels analysed. Body sway signal below 2Hz was consistent between trials, as evident in the large amplitude peak at approximately 0.2Hz. Evident also, but with only a small amplitude, was the 4Hz peak that existed strongly in Fz. This would suggest that only a small amount of canceling of the 4Hz BCG signal will occur when calculating COP.

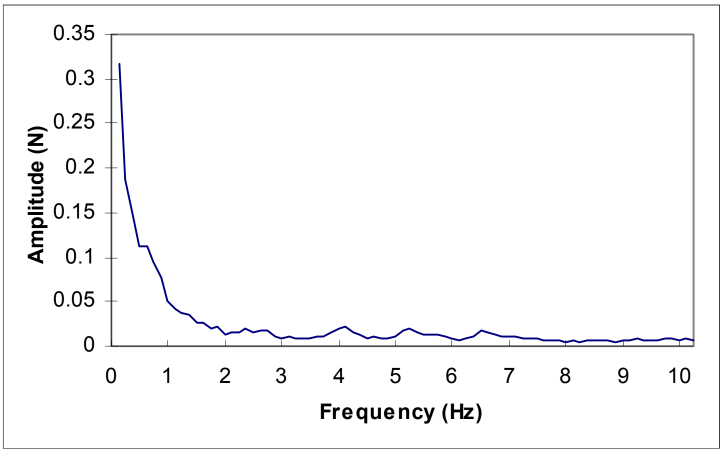

Figure D.16: Ensemble averaged spectrum of My raw data calculated from ten shooting trials over 5s.

Examining the My residual graph (figure D.17) from right to left, a gradual increase in the residual between 10.5Hz and 4Hz precedes a slight upturn from 4Hz to 2Hz. This indicates that either signal exists below 2Hz or no signal exists at all. As already established from the spectral analysis, a large amount of activity exists below 2Hz.

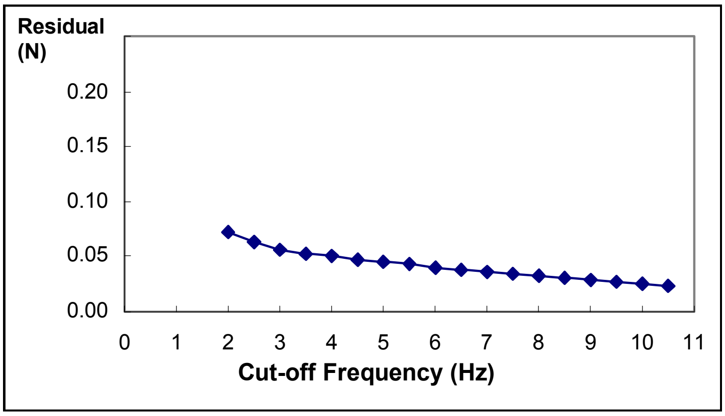

Figure D.17: Residual analysis of My using a range of cut-off frequencies from 2Hz to 10.5Hz.

Note: Other shooters, not reported here, showed signal between 1.5Hz and 3Hz for My.

Mz

Only a very small amount of activity existed in Mz. As can be noted in figure D.18, the amplitude of the peak frequency was only 0.014Nm, which compares with 0.7Nm for My and 0.12Nm in Mx. Further examination of Mz curves indicated that this shooter produced virtually no rotation about the Z-axis.

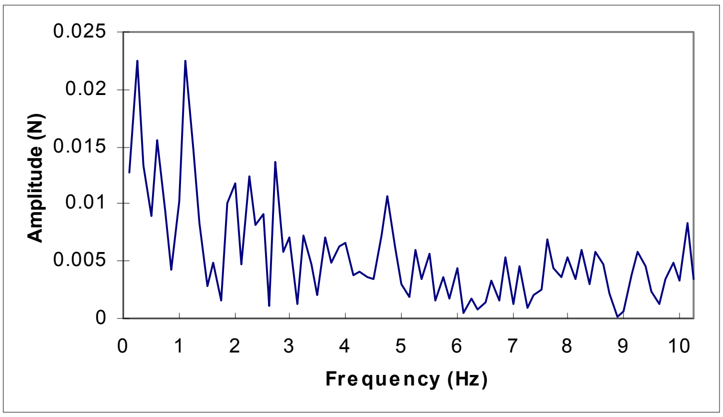

Figure D.18: Amplitude spectrum of Mz raw data calculated from a single rifle-shooting trial over 5s.

The ensemble averaged spectral analysis for Mz (figure D.19) confirms this lack of signal evident in the single trial analysed.

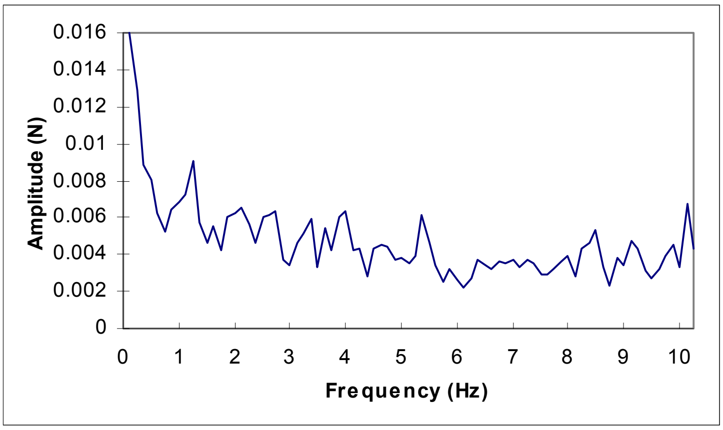

Figure D.19: Ensemble averaged spectrum of Mz raw data calculated from ten shooting trials over 5s.

The Mz residual graph (figure D.20) shows a very slight increase from 10.5Hz to 2Hz, but no upturn of the curve is evident. This indicates that any signal that may exist is well below 2Hz or does not exist at all. As already established, there is only very small amounts of signal in this channel.

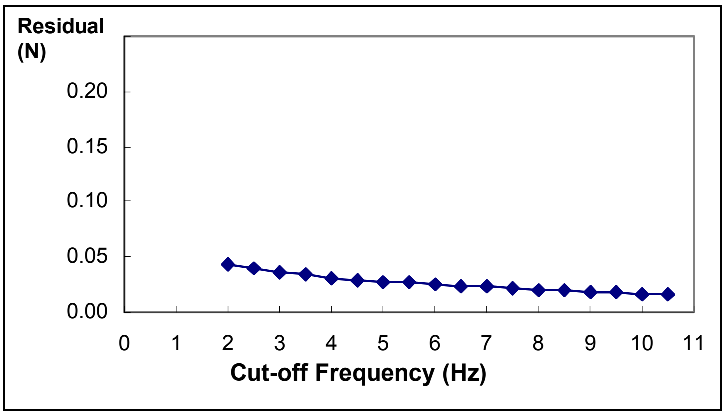

Figure D.20: Residual analysis of Mz using a range of cut-off frequencies from 2Hz to 10.5Hz.

D.2 Analysis of COP signal

COPx

Figure D.21 shows the spectral analysis of COPx calculated using raw data from the rifle-shooting trial over 5s. Most of the activity exists below 2Hz, with a small peak at 2.5Hz. As mentioned, authors have found peaks up to 3Hz for normal subjects (eg. Powell and Dzendolet, 1984; Lucy and Hayes, 1985). As such it was also considered to be body sway. Small peaks also exist at approximately 4Hz and 5.5Hz, with low level activity existing between 4Hz and 7Hz. This was interpreted as being associated with noise, BCG and possibly muscle tremor.

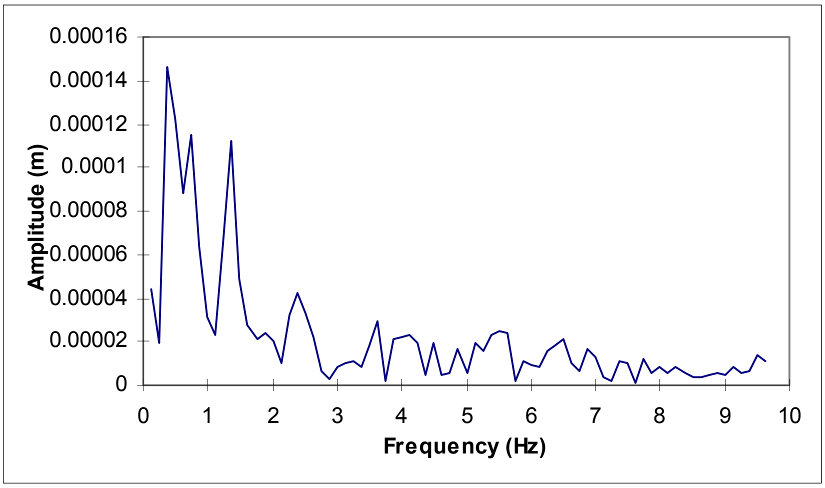

Figure D.21: Amplitude spectrum of COPx calculated using raw data from a single rifle-shooting trial over 5s.

The ensemble averaged spectral analysis for COPx (figure D.22) shows most amplitude in the frequencies below 1Hz. Slight peaks at 4Hz and 5.5Hz indicate these signals are still evident in the COP signal, although at a relatively small amplitude in COPx. This suggests that either the BCG is inconsistent between trials, or that the large My signal is dominant in these calculations. The ensemble average curve is quite different from the individual shot analysed (figure D.21). Different trials showed different frequency peaks between 1Hz and 3Hz. This may have been due to the effects of noise but is more probably due to differences in sway between individual trials. These individual differences may arise from shooters controlling their sway slightly differently between trials as well as differences in slight body adjustments that may be produced as part of the aiming process.

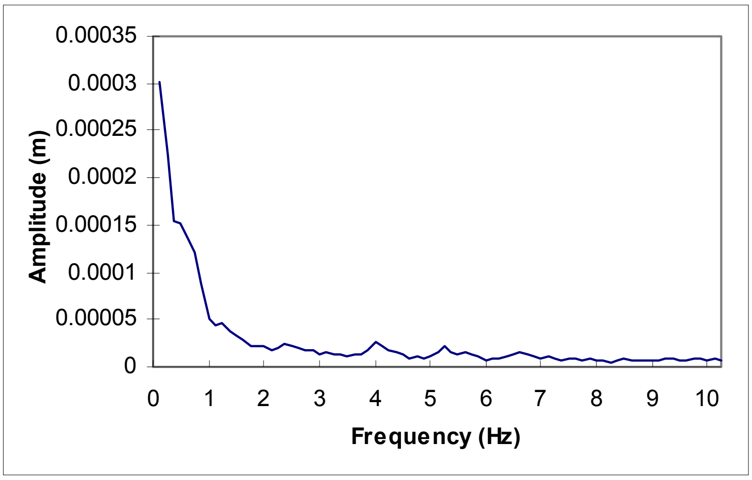

Figure D.22: Ensemble averaged spectrum of COPx calculated using raw data from ten shooting trials over 5s.

COPy

Figure D.23 shows the spectral analysis of COPy calculated using raw data from a rifle-shooting trial over 5s. Large peaks exist below 2Hz, with another large peak existing at approximately 2.75Hz. These were interpreted as being produced by body sway. Once again, the peak above 2Hz is slightly higher than expected but has been found in other research. Amplitudes for peaks below 2Hz were smaller than for COPx indicating the greater movement in COPx. Also, the 2.75Hz peak was slightly greater in amplitude and slightly higher in frequency than the 2.5Hz peak in COPx. This indicates a slightly different nature of movement in COPy compared to COPx. Although the 5.5Hz peak was noticeable, it is unusual that there was no evidence of the 4Hz peak for this trial. This may indicate some canceling of the BCG in calculations, or may be particular to this trial, as the 4Hz peak is evident in the ensemble averaged spectral analysis (figure D.22).

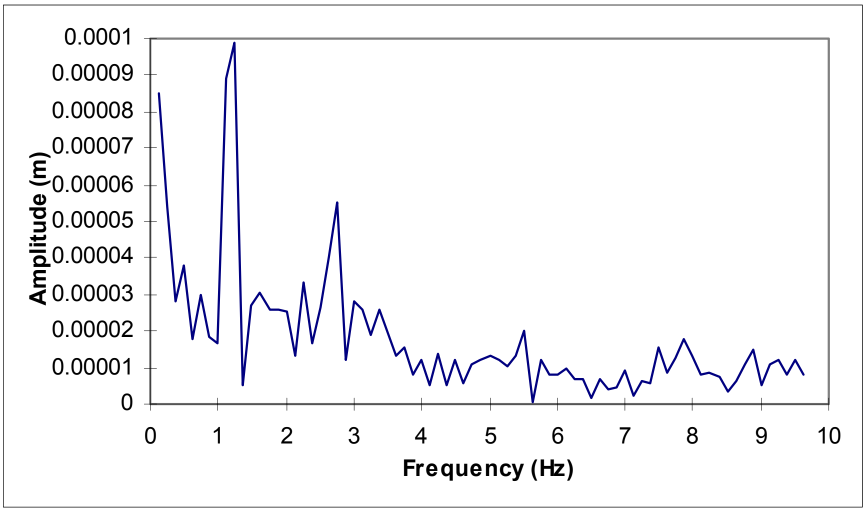

Figure D.23: Amplitude spectrum of COPy calculated using raw data from a single rifle-shooting trial over 5s.

The ensemble averaged spectral analysis for COPx (figure D.22) shows frequency below 1.5Hz. However, overall there is only a small amount of activity in the ensemble averaged spectral analysis of COPy for this rifle shooter (figure D.24). Amplitude of frequencies below 3Hz where sway signal is expected is only moderately larger than the amplitude in higher frequencies. Of particular note in this data is the relatively high 4Hz and 5.5Hz peaks. This indicates the signal in COPy due to sway is small in both absolute terms and relative to noise and signal not associated with sway. While other shooters and other shots for this shooter showed more amplitude of movement below 3Hz, it was still quite low, indicating shooters produce only very small movements in COPy.

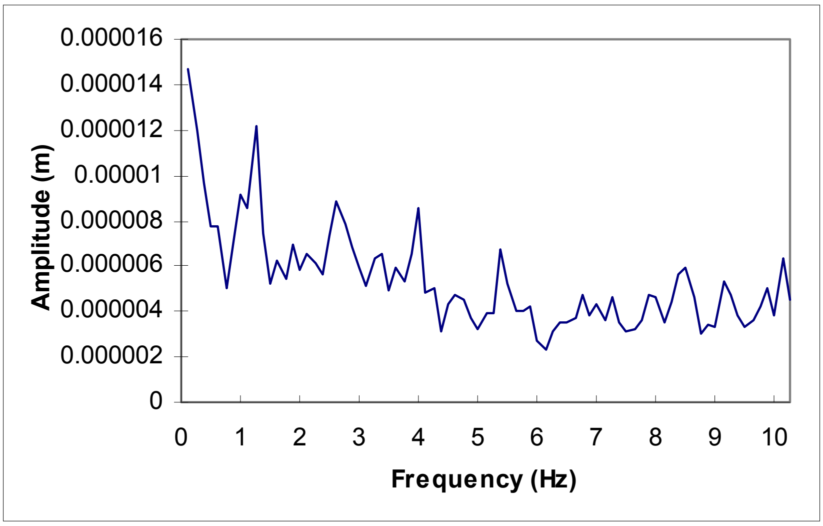

Figure D.24: Ensemble averaged spectrum of COPy calculated using raw data from ten shooting trials over 5s.

D.3 Smoothing summary

On completion of this analysis, a cut-off frequency of 4Hz was decided upon for all channels. Remembering that the nature of the recursive filter will effectively reduce this cut-off to 3.2Hz, the decision of 4Hz was based on the compromise between leaving the COP frequency below 3Hz unchanged, while eliminating as much of the 4Hz BCG signal as possible. Some signal below 3Hz signal will be reduced and some 4Hz signal will pass through the filter, but, as noted by Winter (1990), smoothing is always a trade off between eliminating signal and allowing noise to pass through the smoothing process. Visual inspection of the curves indicated that this smoothing cut-off was appropriate.

Figure D.25 compares COPx curves calculated from raw and smoothed force and moment data for a selected rifle-shooting trial to show the effects of the 4Hz filter.

Figure D.26 compares the spectral analysis of the two curves. As can be noted in figure D.26, activity below 3Hz is unchanged. The 4Hz peak is considerably reduced considerably, while frequencies above this point are almost completely eliminated. This can be related to the COP displacement curve in figure D.25. The relatively high frequency component is eliminated in the COP using smoothed force and moment data, while the low frequency component remains.

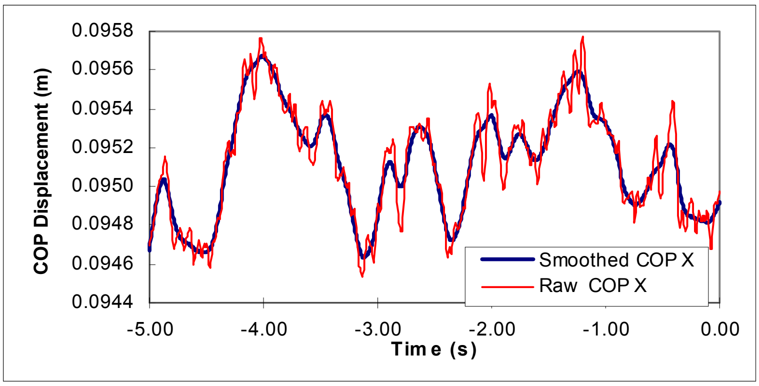

Figure D.25: Raw and smoothed COPx displacement curves over 5s calculated from a rifle-shooting trial.

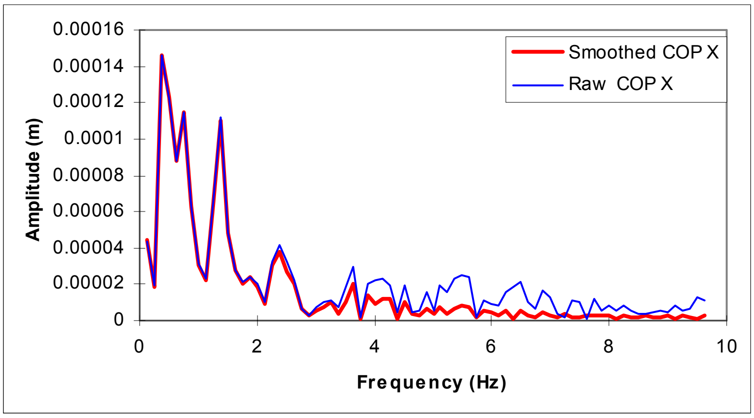

Figure D.26: Spectral analysis of raw and smoothed COPx displacement curves over 5s calculated from a rifle-shooting trial.

Similarly, figures D.27 and D.28 show the same curves as above for COPy. As can be noted in figure D.28, activity below 3Hz is largely unchanged, although some amplitude has been reduced at the 2.75Hz peak and up to 4Hz. There was no 4Hz peak in this trial, although the 5.5Hz peak was almost eliminated from the curve by smoothing force and moment data. Activity above this frequency was also eliminated. Relating back to curve D.27, the relatively 'noisy' looking curve with high frequency, low amplitude noise has been reduced to a smooth low frequency curve that is expected of CG movement during quite stance.

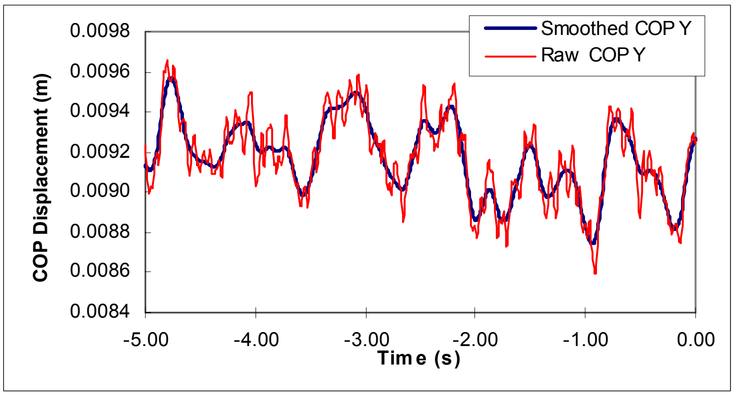

Figure D.27: Raw and smoothed COPy displacement curves over 5s calculated from a rifle-shooting trial.

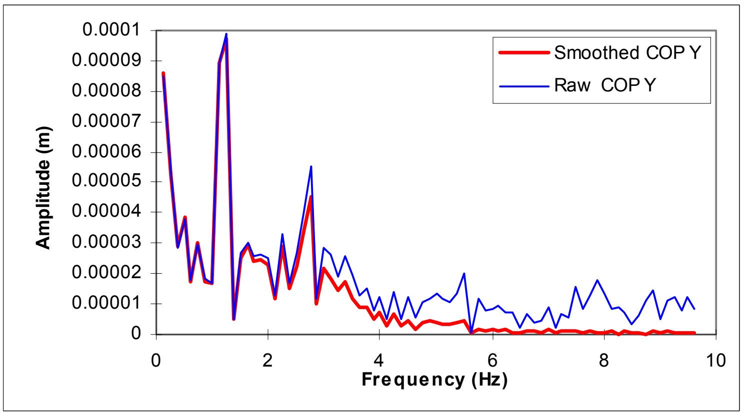

Figure D.28: Spectral analysis of raw and smoothed COPy displacement curves over 5s calculated from a rifle-shooting trial.

Note on non-stationary signals

Some of the signals processed using the FFT were non-stationary. The existence of the BCG and the tendency for shooters to reduce the range of movement during the measurement period meant that the signal in some channels was not entirely repeatable, and did not retain the same variance throughout. Further, quiet stance of non-shooting subjects has been described as a dynamic activity containing random elements (eg. Keogh *et al*., 2000). This presented a potential problem for FFTanalysis.

To further examine the effect that the non-stationary signals had on the spectral analyses of individual channels, 1s and 2s subsets of the 5s trial were formed and a FFT was applied to each. This allowed for a frequency profile of the signal across different time periods to be built, similar to that produced by a Short Term Fourier Transform (STFT), which is used to evaluate non-stationary signals using the FFT. While amplitudes of the peak frequencies were reduced in the smaller periods, compared with the 5s period, similar patterns emerged. The exception was in the time periods that did not contain a BCG signal. Based on this factor, it was felt that the FFT analysis was justified in its use.

It should be noted that for the purpose for which it was used in this study, the FFT analysis was adequate. A FFT of a non-stationary signal will be appropriate if information on the frequency content is required, without information on when in the sequence those frequencies occurred (Polikar, 1996). Polikar showed that the FFT of a non-stationary, compared to a stationary, signal with the same frequency content showed a slight reduction in the amplitude of the peak frequencies and a slight increase the amplitudes of the frequencies surrounding this peak. As an overall estimate of frequency content was required, FFT analysis provided this information adequately for this study.

In summary, while the FFT may not have been the most appropriate algorithm to use to quantify the time course of any changes in the frequency spectrum of the signal, it was used to gain insight into predominant frequencies in the signal. The results were used to better assess an appropriate smoothing cut-off frequency only, and not for an in depth discussion of the frequency content of the signal. While some signals were non-stationary, the FFT provided the required information and, used in conjunction with the residual analysis, formed an appropriate framework for the cut-off decision.

Keogh, J., Morrison, S. and Barrett, R. (2000) Time-varying properties of the COP signal during stance. In ABC3: Book of abstracts (Edited by Barret, R., Simeoni, R. and D'Helen, C.) pp45-46, Gold Coast.

Polikar, R. (1996) The wavelet tutorial (2nd edition) http://www.public.iastate.edu/%7erpolikar/WAVELETS/WTpart1.html

APPENDIX E

Results of Principal Components Analysis (PCA)

R1	1 s			3s	5s		
Factor	1	2	3		1	2	3
FxRange	**-0.03**	**0.10**	**0.95**		**-0.13**	**0.96**	**0.15**
FxSD	**0.05**	**0.02**	**0.96**		**-0.25**	**0.88**	**0.08**
FyRange	**0.95**	**0.05**	**-0.04**		**0.90**	**0.05**	**0.17**
FySD	**0.94**	**0.12**	**-0.02**		**0.95**	**-0.03**	**0.11**
COPxLength	**0.12**	**0.75**	**0.58**		**0.18**	**0.87**	**0.41**
COPxRange	**0.00**	**0.99**	**0.09**		**0.10**	**0.28**	**0.94**
COPxSD	**0.05**	**0.97**	**0.16**		**0.15**	**0.24**	**0.94**
COPyLength	**0.97**	**0.08**	**-0.04**		**0.95**	**0.00**	**-0.16**
COPyRange	**0.97**	**0.11**	**-0.03**		**0.61**	**0.05**	**0.28**
COPySD	**0.96**	**0.13**	**0.05**		**0.85**	**-0.03**	**0.31**
COPAbsLength	**0.91**	**0.35**	**0.19**		**0.75**	**0.62**	**0.19**
COPAbsRange	**0.46**	**0.87**	**0.02**		**0.14**	**0.27**	**0.95**
COPxVelSD	**0.15**	**0.42**	**0.82**		**0.10**	**0.94**	**0.25**
COPyVelSD	**0.98**	**0.01**	**-0.02**		**0.97**	**0.03**	**-0.08**
COPAbsSpeedAve	**0.91**	**0.34**	**0.18**		**0.75**	**0.62**	**0.19**
COPAbsSpeedSD	**0.88**	**-0.12**	**0.33**		**0.44**	**0.79**	**0.23**

R2	1 s				3s		5s
Factor	1	2	3				
FxRange	**0.03**	**0.66**	**0.56**				
FxSD	**-0.06**	**0.66**	**0.53**				
FyRange	**0.85**	**-0.07**	**0.26**				
FySD	**0.92**	**-0.04**	**0.26**				
COPxLength	**0.07**	**0.50**	**0.79**				
COPxRange	**0.00**	**0.97**	**0.17**				
COPxSD	**-0.04**	**0.96**	**0.18**				
COPyLength	**0.94**	**-0.02**	**0.15**				
COPyRange	**0.93**	**0.14**	**-0.21**				
COPySD	**0.91**	**0.06**	**-0.14**				
COPAbsLength	**0.78**	**0.29**	**0.53**				
COPAbsRange	**0.25**	**0.95**	**0.10**				
COPxVelSD	**0.14**	**0.19**	**0.93**				
COPyVelSD	**0.97**	**-0.04**	**0.14**				
COPAbsSpeedAve	**0.78**	**0.29**	**0.52**				
COPAbsSpeedSD	**0.56**	**0.19**	**0.68**				

R3	1 s		3s		5s	
Factor	1	2	1	2	1	2
FxRange	**0.98**	**0.09**	**0.92**	**0.10**	**0.89**	**0.15**
FxSD	**0.99**	**0.00**	**0.95**	**0.09**	**0.91**	**0.24**
FyRange	**0.21**	**0.94**	**0.07**	**0.95**	**-0.05**	**0.89**
FySD	**0.33**	**0.92**	**0.25**	**0.96**	**0.14**	**0.98**
COPxLength	**0.99**	**0.04**	**0.98**	**0.12**	**0.95**	**0.18**
COPxRange	**0.96**	**0.14**	**0.93**	**0.16**	**0.92**	**-0.13**
COPxSD	**0.97**	**0.07**	**0.91**	**0.16**	**0.89**	**-0.07**
COPyLength	**-0.04**	**0.98**	**-0.01**	**0.98**	**-0.02**	**0.97**
COPyRange	**0.09**	**0.97**	**0.36**	**0.85**	**0.56**	**0.57**
COPySD	**0.16**	**0.98**	**0.33**	**0.92**	**0.34**	**0.88**
COPAbsLength	**0.76**	**0.64**	**0.69**	**0.70**	**0.72**	**0.66**
COPAbsRange	**0.92**	**0.33**	**0.92**	**0.24**	**0.92**	**-0.07**
COPxVelSD	**0.97**	**-0.03**	**0.98**	**0.08**	**0.95**	**0.16**
COPyVelSD	**-0.04**	**0.98**	**-0.03**	**0.99**	**-0.04**	**0.97**
COPAbsSpeedAve	**0.76**	**0.64**	**0.69**	**0.70**	**0.72**	**0.66**
COPAbsSpeedSD	**0.92**	**0.30**	**0.84**	**0.44**	**0.86**	**0.42**

R4	1 s	3s			5s		
Factor		1	2	3	1	2	3
FxRange		**0.14**	**0.91**	**0.22**	**0.33**	**0.85**	**0.21**
FxSD		**0.14**	**0.93**	**0.25**	**0.17**	**0.91**	**0.31**
FyRange		**0.89**	**0.15**	**0.00**	**0.87**	**0.34**	**-0.13**
FySD		**0.90**	**0.33**	**-0.04**	**0.91**	**0.33**	**-0.14**
COPxLength		**0.18**	**0.93**	**0.07**	**0.26**	**0.91**	**0.29**
COPxRange		**0.02**	**0.17**	**0.98**	**0.02**	**0.38**	**0.92**
COPxSD		**-0.03**	**0.08**	**0.98**	**-0.09**	**0.14**	**0.95**
COPyLength		**0.94**	**0.18**	**-0.01**	**0.94**	**0.20**	**-0.07**
COPyRange		**0.93**	**0.06**	**0.16**	**0.86**	**0.19**	**0.27**
COPySD		**0.89**	**0.18**	**0.00**	**0.90**	**0.20**	**0.14**
COPAbsLength		**0.69**	**0.70**	**0.04**	**0.65**	**0.71**	**0.18**
COPAbsRange		**0.13**	**0.16**	**0.97**	**0.09**	**0.38**	**0.91**
COPxVelSD		**0.23**	**0.95**	**0.03**	**0.31**	**0.90**	**0.30**
COPyVelSD		**0.96**	**0.10**	**0.02**	**0.96**	**0.17**	**-0.08**
COPAbsSpeedAve		**0.69**	**0.70**	**0.04**	**0.65**	**0.71**	**0.18**
COPAbsSpeedSD		**0.67**	**0.39**	**0.29**	**0.66**	**0.50**	**0.25**

R5	1 s		3s	5s		
Factor	1	2		1	2	
FxRange	**0.95**	**0.10**		**0.93**	**0.13**	**0.07**
FxSD	**0.91**	**0.02**		**0.88**	**0.08**	**0.16**
FyRange	**0.20**	**0.94**		**0.00**	**0.58**	**0.72**
FySD	**0.12**	**0.96**		**0.24**	**0.84**	**0.38**
COPxLength	**0.95**	**0.19**		**0.97**	**0.14**	**0.05**
COPxRange	**0.95**	**0.09**		**0.93**	**0.06**	**0.18**
COPxSD	**0.97**	**0.03**		**0.90**	**-0.03**	**0.16**
COPyLength	**0.01**	**0.97**		**0.12**	**0.96**	**0.15**
COPyRange	**0.16**	**0.89**		**0.14**	**0.19**	**0.94**
COPySD	**0.20**	**0.90**		**0.46**	**0.36**	**0.69**
COPAbsLength	**0.76**	**0.63**		**0.86**	**0.48**	**0.05**
COPAbsRange	**0.92**	**0.23**		**0.92**	**0.06**	**0.21**
COPxVelSD	**0.93**	**0.20**		**0.98**	**0.10**	**0.03**
COPyVelSD	**0.02**	**0.96**		**0.06**	**0.96**	**0.21**
COPAbsSpeedAve	**0.76**	**0.63**		**0.86**	**0.48**	**0.05**
COPAbsSpeedSD	**0.49**	**0.59**		**0.86**	**0.10**	**0.14**

R6	1 s				3s				5s
Factor	1	2	3		1	2	3		
FxRange	**0.04**	**0.96**	**0.16**		**-0.09**	**0.94**	**0.01**		
FxSD	**0.11**	**0.94**	**0.22**		**-0.25**	**0.93**	**0.12**		
FyRange	**0.84**	**0.05**	**-0.19**		**0.56**	**-0.07**	**-0.55**		
FySD	**0.87**	**0.12**	**-0.08**		**0.86**	**-0.09**	**-0.26**		
COPxLength	**-0.04**	**0.91**	**0.34**		**-0.08**	**0.88**	**0.37**		
COPxRange	**-0.04**	**0.27**	**0.95**		**-0.26**	**0.21**	**0.93**		
COPxSD	**-0.12**	**0.23**	**0.95**		**-0.42**	**0.15**	**0.88**		
COPyLength	**0.95**	**-0.09**	**0.02**		**0.91**	**-0.27**	**-0.24**		
COPyRange	**0.92**	**-0.12**	**0.17**		**0.77**	**-0.41**	**-0.24**		
COPySD	**0.94**	**-0.05**	**0.16**		**0.90**	**-0.17**	**-0.28**		
COPAbsLength	**0.85**	**0.43**	**0.15**		**0.95**	**0.23**	**-0.11**		
COPAbsRange	**0.30**	**0.17**	**0.93**		**-0.19**	**0.15**	**0.96**		
COPxVelSD	**0.01**	**0.97**	**0.06**		**0.02**	**0.94**	**0.11**		
COPyVelSD	**0.98**	**-0.09**	**-0.02**		**0.90**	**-0.29**	**-0.29**		
COPAbsSpeedAve	**0.84**	**0.44**	**0.14**		**0.95**	**0.23**	**-0.12**		
COPAbsSpeedSD	**0.79**	**0.03**	**-0.01**		**0.81**	**-0.31**	**-0.29**		

P1	1 s	
Factor	1	2
FxRange	**0.94**	**0.13**
FxSD	**0.92**	**0.18**
FyRange	**0.11**	**0.96**
FySD	**0.12**	**0.98**
COPxLength	**0.87**	**0.27**
COPxRange	**0.93**	**-0.02**
COPxSD	**0.89**	**-0.09**
COPyLength	**0.24**	**0.96**
COPyRange	**0.17**	**0.96**
COPySD	**0.16**	**0.97**
COPAbsLength	**0.75**	**0.62**
COPAbsRange	**0.88**	**0.31**
COPxVelSD	**0.87**	**0.29**
COPyVelSD	**0.22**	**0.96**
COPAbsSpeedAve	**0.75**	**0.62**
COPAbsSpeedSD	**0.76**	**0.28**

P2	1 s		
Factor	1	2	3
FxRange	**0.50**	**0.29**	**0.72**
FxSD	**0.43**	**0.30**	**0.75**
FyRange	**-0.02**	**0.88**	**0.19**
FySD	**-0.06**	**0.89**	**0.20**
COPxLength	**0.78**	**0.00**	**0.58**
COPxRange	**0.97**	**-0.01**	**0.18**
COPxSD	**0.97**	**0.01**	**0.13**
COPyLength	**0.03**	**0.94**	**0.25**
COPyRange	**0.36**	**0.87**	**-0.08**
COPySD	**0.32**	**0.86**	**-0.13**
COPAbsLength	**0.63**	**0.42**	**0.62**
COPAbsRange	**0.98**	**0.10**	**0.13**
COPxVelSD	**0.04**	**-0.02**	**0.94**
COPyVelSD	**0.07**	**0.93**	**0.25**
COPAbsSpeedAve	**0.63**	**0.42**	**0.62**
COPAbsSpeedSD	**0.76**	**0.24**	**0.18**

P3	1 s		
Factor	1	2	3
FxRange	**0.03**	**0.80**	**0.44**
FxSD	**-0.06**	**0.84**	**0.39**
FyRange	**0.95**	**-0.01**	**-0.15**
FySD	**0.95**	**-0.01**	**-0.23**
COPxLength	**0.04**	**0.72**	**0.63**
COPxRange	**-0.18**	**0.28**	**0.93**
COPxSD	**-0.22**	**0.36**	**0.89**
COPyLength	**0.98**	**-0.01**	**-0.07**
COPyRange	**0.86**	**-0.31**	**-0.07**
COPySD	**0.86**	**-0.35**	**0.02**
COPAbsLength	**0.89**	**0.35**	**0.24**
COPAbsRange	**0.22**	**0.17**	**0.95**
COPxVelSD	**0.08**	**0.92**	**0.09**
COPyVelSD	**0.97**	**-0.04**	**-0.08**
COPAbsSpeedAve	**0.89**	**0.35**	**0.23**
COPAbsSpeedSD	**0.72**	**0.33**	**0.04**

P4	1 s		
Factor	1	2	3
FxRange	**0.97**	**0.02**	**0.11**
FxSD	**0.94**	**-0.07**	**0.09**
FyRange	**0.26**	**0.57**	**-0.60**
FySD	**0.07**	**0.65**	**-0.64**
COPxLength	**0.84**	**0.11**	**0.49**
COPxRange	**0.44**	**0.04**	**0.85**
COPxSD	**0.37**	**-0.03**	**0.85**
COPyLength	**0.05**	**0.97**	**-0.04**
COPyRange	**0.07**	**0.95**	**0.05**
COPySD	**0.16**	**0.92**	**0.03**
COPAbsLength	**0.77**	**0.45**	**0.43**
COPAbsRange	**0.43**	**0.18**	**0.85**
COPxVelSD	**0.96**	**0.10**	**0.05**
COPyVelSD	**0.07**	**0.94**	**0.06**
COPAbsSpeedAve	**0.77**	**0.44**	**0.42**
COPAbsSpeedSD	**0.86**	**0.21**	**0.38**

P5	1 s	
Factor	1	2
FxRange	**-0.07**	**0.96**
FxSD	**0.05**	**0.97**
FyRange	**0.95**	**0.11**
FySD	**0.96**	**0.09**
COPxLength	**0.25**	**0.93**
COPxRange	**0.12**	**0.93**
COPxSD	**0.17**	**0.89**
COPYLength	**0.97**	**0.17**
COPYRange	**0.94**	**0.14**
COPYSD	**0.94**	**0.15**
COPAbsLength	**0.73**	**0.66**
COPAbsRange	**0.33**	**0.88**
COPxVelSD	**0.33**	**0.78**
COPYVelSD	**0.97**	**0.19**
COPAbsSpeedAve	**0.73**	**0.66**
COPAbsSpeedSD	**0.60**	**0.62**

APPENDIX F

Statistical analyses (correlations and multiple regressions) between body sway, aim point and shooting performance parameters for all shooters

R1

Table F.1: Correlation Matrix: Body sway data and shot result data for R1

	Result	PosX	PosY
COPxLength s5	**0.06**	**-0.14**	**0.22**
COPxRange s5	**-0.18**	**0.14**	**0.25**
COPyLength s5	**0.41**	**-0.38**	**-0.05**
COPyRange s5	**0.30**	**-0.41**	**0.13**
COPxLength s3	**0.05**	**0.00**	**0.06**
COPxRange s3	**-0.03**	**0.14**	**-0.04**
COPyLength s3	**0.35**	**-0.30**	**-0.13**
COPyRange s3	**0.42**	**-0.42**	**-0.16**
COPxLength s1	**0.13**	**-0.03**	**-0.12**
COPxRange s1	**0.23**	**-0.14**	**-0.24**
COPyLength s1	**0.10**	**-0.04**	**-0.09**
COPyRange s1	**0.14**	**-0.05**	**-0.12**

Table F.2: Correlation Matrix: Aim point data and shot result data for R1

	Result	PosX	PosY
Std10.0 s5	**0.13**	**0.02**	**-0.30**
Std10a0 s5	**0.00**	**0.17**	**-0.25**
Length s5	**0.20**	**-0.38**	**0.23**
LengthX s5	**0.29**	**-0.41**	**0.13**
LengthY s5	**-0.10**	**-0.17**	**0.41**
Std10.0 s3	**0.30**	**-0.16**	**-0.30**
Std10a0 s3	**-0.07**	**0.26**	**-0.22**
Length s3	**-0.10**	**-0.08**	**0.36**
LengthX s3	**0.02**	**-0.11**	**0.23**
LengthY s3	**-0.22**	**-0.04**	**0.39**
Std10.0 s1	**0.41**	**-0.27**	**-0.30**
Std10a0 s1	**0.10**	**-0.01**	**-0.21**
Length s1	**-0.17**	**0.16**	**0.25**
LengthX s1	**0.16**	**-0.06**	**-0.02**
LengthY s1	**-0.55***	**0.37**	**0.53***

Table F.3: Correlation Matrix: Aim point data and body sway data for R1

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s5	**-0.43**	**-0.51***	**0.06**	**-0.54***
Std10a0 s5	**-0.55***	**-0.33**	**0.09**	**-0.45***
Length s5	**0.65****	**0.24**	**0.35**	**0.58****
LengthX s5	**0.73****	**0.20**	**0.31**	**0.49***
LengthY s5	**0.20**	**0.24**	**0.27**	**0.57****
Std10.0 s3	**-0.56***	**-0.44**	**0.43**	**0.08**
Std10a0 s3	**-0.18**	**-0.21**	**0.13**	**-0.15**
Length s3	**0.36**	**0.32**	**0.14**	**0.33**
LengthX s3	**0.34**	**0.29**	**0.23**	**0.24**
LengthY s3	**0.24**	**0.21**	**-0.08**	**0.37**
Std10.0 s1	**-0.06**	**-0.05**	**0.25**	**0.23**

Std10a0 s1	**-0.35**	**-0.52***	**-0.17**	**-0.10**
Length s1	**0.08**	**0.01**	**0.25**	**0.14**
LengthX s1	**0.28**	**0.24**	**0.31**	**0.22**
LengthY s1	**-0.24**	**-0.29**	**0.09**	**0.02**

Table F.4: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for R1

	v	R^2	p	Cv	Regression Equation
Result	**1**	**16.5**	**0.08**	**0.9**	7.57 + 0.151 COPyLength s5
PosX	**2**	**23**	**0.11**	**2.7**	5.83 + 0.259 COPxRange s5 - 2.93 COPyRange s5
PosY	**1**	**6.2**	**0.29**	**-0.7**	1.03 + 0.227 COPxRange s5
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**1**	**17.5**	**0.07**	**-0.4**	7.64 + 1.56 COPyRange s3
PosX	**1**	**17.6**	**0.07**	**-0.2**	7.04 - 3.69 COPyRange s3
PosY	**1**	**2.5**	**0.50**	**0**	3.45 - 1.23 COPyRange s3
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**1**	**5.3**	**0.33**	**-0.4**	9.35 + 0.36 COPxRange s1
PosX	**1**	**1.9**	**0.56**	**-0.7**	2.7 - 0.502 COPxRange s1
PosY	**1**	**6**	**0.30**	**-0.4**	2.54 - 0.789 COPxRange s1
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**2**	**13.9**	**0.28**	**1.2**	9.2 + 0.0273 LengthX s5 - 0.0335 LengthY s5
PosX	**1**	**16.9**	**0.07**	**-1**	7.64 - 0.0666 LengthX s5
PosY	**1**	**17**	**0.07**	**-0.6**	- 3.95 + 0.112 LengthY s5
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**1**	**8.7**	**0.26**	**-0.3**	9.29 + 0.0137 Std10.0 s3
PosX	**1**	**6.7**	**0.27**	**-0.4**	1.16 + 0.0248 Std10a0 s3
PosY	**1**	**15.4**	**0.09**	**0.1**	- 2.48 + 0.145 LengthY s3
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**2**	**41.3**	**0.01**	**1.8**	10.4 + 0.109 LengthX s1 - 0.248 LengthY s1
PosX	**1**	**13.7**	**0.11**	**-0.2**	- 0.73 + 0.329 LengthY s1
PosY	**1**	**28.5**	**0.02**	**0.9**	- 1.97 + 0.419 LengthY s1
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0 s5	**3**	**50.2**	**0.01**	**3.1**	46.9 - 3.01 COPxRange s5 + 1.78 COPyLength s5 - 26.5 COPyRange s5
Std10a0 s5	**3**	**45.7**	**0.02**	**3.2**	64.4 - 2.49 COPxLength s5 + 2.14 COPyLength s5 - 22.7 COPyRange s5
LengthX s5	**3**	**74.3**	**0.00**	**3.9**	35.5 + 3.84 COPxLength s5 - 2.97 COPxRange s5 + 12.3
LengthY s5	**1**	**33.1**	**0.01**	**-0.6**	33.9 + 11.6 COPyRange s5
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0 s3	**2**	**41.2**	**0.01**	**1.7**	27.5 - 5.59 COPxLength s3 + 3.76 COPyLength s3
Std10a0 s3	**1**	**4.4**	**0.38**	**-0.1**	51.5 - 2.59 COPxRange s3
LengthX s3	**2**	**20.4**	**0.14**	**1.2**	24.3 + 1.82 COPxLength s3 + 1.4 COPyLength s3
LengthY s3	**2**	**22.9**	**0.11**	**1.2**	23.4 - 1.04 COPyLength s3 + 11.5 COPyRange s3
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0 s1	**1**	**6**	**0.30**	**-0.9**	28.9 + 8.08 COPyLength s1
Std10a0 s1	**1**	**27.4**	**0.02**	**0.5**	87.4 - 8.99 COPxRange s1
LengthX s1	**3**	**24.2**	**0.21**	**3**	10.3 + 1.41 COPxLength s1 + 3.6 COPyLength s1 - 8.77 COPyRange s1
LengthY s1	**1**	**8.6**	**0.21**	**0.1**	10.2 - 1.21 COPxRange s1

R3

Table F.5: Correlation Matrix: Body sway data and shot result data for R3

	Result	PosX	PosY
COPxLength s5	**0.14**	**-0.11**	**-0.10**
COPxRange s5	**0.20**	**-0.20**	**-0.14**
COPyLength s5	**-0.57****	**0.58****	**-0.10**
COPyRange s5	**-0.22**	**0.28**	**-0.12**
COPxLength s3	**0.08**	**-0.06**	**-0.08**
COPxRange s3	**0.09**	**-0.06**	**-0.10**
COPyLength s3	**-0.54***	**0.54***	**0.01**
COPyRange s3	**-0.46***	**0.51***	**-0.01**
COPxLength s1	**0.22**	**-0.16**	**-0.25**
COPxRange s1	**0.03**	**0.02**	**-0.16**
COPyLength s1	**-0.40**	**0.37**	**0.08**
COPyRange s1	**-0.29**	**0.30**	**-0.02**

Table F.6: Correlation Matrix: Aim point data and shot result data for R3.

	Result	PosX	PosY
Std10.0 s5	**0.07**	**-0.08**	**0.11**
Std10a0 s5	**0.10**	**0.02**	**-0.22**
Length s5	**-0.17**	**0.11**	**0.04**
LengthX s5	**-0.26**	**0.33**	**-0.21**
LengthY s5	**0.05**	**-0.20**	**0.26**
Std10.0 s3	**0.25**	**-0.28**	**0.25**
Std10a0 s3	**0.40**	**-0.42**	**0.17**
Length s3	**-0.01**	**0.04**	**0.03**
LengthX s3	**-0.03**	**0.10**	**-0.06**
LengthY s3	**0.01**	**-0.08**	**0.17**
Std10.0 s1	**0.33**	**-0.31**	**0.06**
Std10a0 s1	**0.32**	**-0.29**	**0.13**
Length s1	**0.06**	**-0.01**	**-0.22**
LengthX s1	**-0.02**	**0.11**	**-0.29**
LengthY s1	**0.15**	**-0.19**	**0.03**

Table F.7: Correlation Matrix: Aim point data and body sway data for R3.

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s5	**-0.06**	**-0.35**	**-0.02**	**-0.05**
Std10a0 s5	**0.27**	**0.03**	**-0.02**	**0.26**
Length s5	**0.07**	**0.13**	**0.23**	**-0.16**
LengthX s5	**0.30**	**0.28**	**0.30**	**0.17**
LengthY s5	**-0.29**	**-0.20**	**-0.03**	**-0.42**
Std10.0 s3	**-0.25**	**-0.34**	**-0.08**	**-0.21**
Std10a0 s3	**-0.18**	**-0.22**	**0.03**	**-0.14**
Length s3	**0.59****	**0.58****	**-0.16**	**0.14**
LengthX s3	**0.64****	**0.66****	**-0.08**	**0.33**
LengthY s3	**0.04**	**-0.05**	**-0.25**	**-0.43**
Std10.0 s1	**0.24**	**0.30**	**0.08**	**0.08**
Std10a0 s1	**0.08**	**0.16**	**0.07**	**0.04**
Length s1	**0.30**	**0.09**	**-0.20**	**-0.18**
LengthX s1	**0.32**	**0.11**	**-0.15**	**-0.04**
LengthY s1	**0.05**	**-0.05**	**-0.19**	**-0.35**

Table F.8: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for R3

	v	R^2	p	Cv	Regression Equation
Result	**2**	**37.5**	**0.03**	**1.1**	11.1 + 0.0313 COPxLength s5 - 0.123 COPyLength s5
PosX	**2**	**36.9**	**0.03**	**1.4**	5.83 + 0.259 COPxRange s5 - 2.93 COPyRange s5
PosY	**1**	**1.9**	**0.58**	**-0.8**	0.978 - 0.0484 COPxRange s5
	v	R^2	p	Cv	Regression Equation
Result	**2**	**36.5**	**0.03**	**1.3**	11.1 + 0.275 COPxRange s3 - 1.64 COPyRange s3
PosX	**2**	**40.9**	**0.02**	**1.1**	- 1.42 - 0.726 COPxRange s3 + 4.7 COPyRange s3
PosY	**1**	**0.9**	**0.70**	**-1**	0.925 - 0.049 COPxRange s3
	v	R^2	p	Cv	Regression Equation
Result	**3**	**38.6**	**0.07**	**3**	10.1 + 0.713 COPxLength s1 - 0.895 COPxRange s1 - 0.171 COPyLength s1
PosX	**2**	**26.7**	**0.10**	**2.1**	2.58 - 2.03 COPxLength s1 + 2.7 COPxRange s1
PosY	**1**	**6.3**	**0.31**	**-0.1**	1.03 - 0.111 COPxLength s1
	v	R^2	p	Cv	Regression Equation
Result	**1**	**7**	**0.29**	**0.5**	11.9 - 0.0261 LengthX s5
PosX	**1**	**10.8**	**0.18**	**0.5**	- 4.43 + 0.0871 LengthX s5
PosY	**1**	**7**	**0.29**	**-0.1**	- 0.221 + 0.0209 LengthY s5
	v	R^2	p	Cv	Regression Equation
Result	**2**	**23.8**	**0.13**	**1.3**	8.02 - 0.0387 Std10.0 s3 + 0.0639 Std10a0 s3
PosX	**2**	**24.1**	**0.13**	**1.6**	7.59 + 0.0928 Std10.0 s3 - 0.165 Std10a0 s3
PosY	**1**	**6**	**0.33**	**-0.2**	0.003 + 0.0116 Std10.0 s3
	v	R^2	p	Cv	Regression Equation
Result	**1**	**10.6**	**0.19**	**0.6**	8.81 + 0.0158 Std10.0 s1
PosX	**2**	**17.2**	**0.24**	**1.1**	12 - 0.074 Std10a0 s1 - 0.377 LengthY s1
PosY	**1**	**8.5**	**0.24**	**-0.5**	1.93 - 0.0806 LengthX s1
	v	R^2	p	Cv	Regression Equation
Std10.0 s5	**2**	**21.4**	**0.16**	**2**	62.1 + 1.13 COPxLength s5 - 4.75 COPxRange s5
Std10a0 s5	**4**	**27.2**	**0.35**	**5**	53.4 + 2.42 COPxLength s5 - 8.13 COPxRange s5 - 2.35 COPyLength s5 + 26.4 COPyRange s5
LengthX s5	**2**	**18.5**	**0.22**	**1.9**	60.1 + 1.26 COPxRange s5 + 0.687 COPyLength s5
LengthY s5	**1**	**17.8**	**0.08**	**0.4**	60.2 - 8.68 COPyRange s5
	v	R^2	p	Cv	Regression Equation
Std10.0 s3	**1**	**11.7**	**0.17**	**-0.6**	78.2 - 3.70 COPxRange s3
Std10a0 s3	**1**	**4.9**	**0.38**	**-0.6**	78.9 - 2.14 COPxRange s3
LengthX s3	**3**	**51.8**	**0.01**	**3.2**	34.8 + 0.839 COPxLength s3 - 1.26 COPyLength s3 +
LengthY s3	**3**	**30.4**	**0.16**	**3.1**	31.8 + 0.406 COPxLength s3 + 0.495 COPyLength s3 -
	v	R^2	p	Cv	Regression Equation
Std10.0 s1	**1**	**8.7**	**0.23**	**-0.8**	72.2 + 4.38 COPxRange s1
Std10a0 s1	**1**	**2.6**	**0.53**	**-0.4**	87.2 + 1.62 COPxRange s1
LengthX s1	**2**	**38.4**	**0.03**	**1**	12.7 + 2.76 COPxLength s1 - 3.38 COPxRange s1
LengthY s1	**4**	**40.3**	**0.13**	**5**	9.48 + 1.45 COPxLength s1 - 1.71 COPxRange s1 + 1.89 COPyLength s1 - 6.62 COPyRange s1

R4

Table F.9: Correlation Matrix: Body sway data and shot result data for R4

	Result	PosX	PosY
COPxLength s5	**0.04**	**-0.09**	**0.06**
COPxRange s5	**0.22**	**-0.16**	**-0.14**
COPyLength s5	**0.15**	**-0.23**	**0.13**
COPyRange s5	**0.22**	**-0.43**	**0.20**
COPxLength s3	**0.13**	**0.05**	**-0.29**
COPxRange s3	**0.23**	**-0.16**	**-0.16**
COPyLength s3	**-0.02**	**-0.12**	**0.21**
COPyRange s3	**0.09**	**-0.22**	**0.14**
COPxLength s1	**0.09**	**-0.01**	**-0.13**
COPxRange s1	**-0.26**	**0.24**	**0.14**
COPyLength s1	**-0.36**	**0.34**	**0.19**
COPyRange s1	**-0.35**	**0.19**	**0.35**

Table F.10: Correlation Matrix: Aim point data and shot result data for R4

	Result	PosX	PosY
Std10.0 s5	**0.50***	**-0.37**	**-0.33**
Std10a0 s5	**0.14**	**-0.18**	**-0.07**
Length s5	**-0.13**	**-0.20**	**0.45***
LengthX s5	**-0.10**	**-0.13**	**0.30**
LengthY s5	**-0.15**	**-0.19**	**0.47***
Std10.0 s3	**0.25**	**-0.15**	**-0.13**
Std10a0 s3	**-0.04**	**-0.01**	**0.12**
Length s3	**0.03**	**-0.30**	**0.37**
LengthX s3	**0.10**	**-0.27**	**0.21**
LengthY s3	**-0.15**	**-0.21**	**0.46***
Std10.0 s1	**0.46***	**-0.35**	**-0.30**
Std10a0 s1	**0.08**	**0.04**	**-0.19**
Length s1	**-0.17**	**0.02**	**0.25**
LengthX s1	**-0.06**	**0.04**	**0.07**
LengthY s1	**-0.19**	**0.01**	**0.20**

Table F.11: Correlation Matrix: Aim point data and body sway data for R4

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s5	**0.29**	**0.08**	**0.17**	**0.22**
Std10a0 s5	**0.05**	**0.02**	**0.06**	**0.02**
Length s5	**0.27**	**-0.23**	**0.52***	**0.42**
LengthX s5	**0.03**	**-0.29**	**0.36**	**0.27**
LengthY s5	**0.48***	**-0.07**	**0.45***	**0.41**
Std10.0 s3	**0.08**	**-0.42**	**-0.16**	**-0.20**
Std10a0 s3	**-0.04**	**-0.22**	**-0.31**	**-0.46***
Length s3	**0.11**	**0.08**	**0.57****	**0.56****
LengthX s3	**0.03**	**0.07**	**0.45***	**0.43**
LengthY s3	**0.23**	**0.09**	**0.44**	**0.48***
Std10.0 s1	**0.21**	**-0.31**	**-0.18**	**0.05**
Std10a0 s1	**0.35**	**0.05**	**-0.34**	**-0.03**
Length s1	**0.21**	**0.10**	**0.59****	**0.29**
LengthX s1	**-0.12**	**-0.26**	**0.23**	**-0.22**
LengthY s1	**0.50***	**0.43**	**0.53***	**0.62****

Table F.12: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for R4

	v	R^2	p	Cv	Regression Equation
Result	**1**	**4.9**	**0.35**	**0.2**	9.91 + 0.0713 COPxRange s5
PosX	**1**	**18.1**	**0.06**	**-0.2**	3.84 - 1.56 COPyRange s5
PosY	**1**	**4.2**	**0.39**	**0.3**	0.104 + 0.541 COPyRange s5
	v	R^2	p	Cv	Regression Equation
Result	**1**	**5.3**	**0.33**	**-0.6**	9.95 + 0.0988 COPxRange s3
PosX	**1**	**4.8**	**0.35**	**-0.3**	2.65 - 0.96 COPyRange s3
PosY	**2**	**18.5**	**0.18**	**1.2**	1.33 - 0.252 COPxLength s3 + 0.194 COPyLength s3
	v	R^2	p	Cv	Regression Equation
Result	**3**	**30.6**	**0.11**	**3.2**	10.4 + 0.456 COPxLength s1 - 0.5 COPxRange s1 - 0.2 COPyLength s1
PosX	**1**	**11.4**	**0.15**	**0.9**	- 0.097 + 0.629 COPyLength s1
PosY	**2**	**20.3**	**0.15**	**2.4**	0.854 - 0.459 COPxLength s1 + 1.35 COPyRange s1
	v	R^2	p	Cv	Regression Equation
Result	**1**	**25.4**	**0.02**	**0.4**	9.23 + 0.0212 Std10.0 s5
PosX	**1**	**13.3**	**0.11**	**-0.1**	3.22 - 0.0402 Std10.0 s5
PosY	**2**	**37.4**	**0.02**	**1.2**	- 2.4 - 0.0309 Std10.0 s5 + 0.105 LengthY s5
	v	R^2	p	Cv	Regression Equation
Result	**1**	**6.2**	**0.29**	**0.6**	9.83 + 0.00683 Std10.0 s3
PosX	**1**	**7.1**	**0.26**	**0.4**	3.54 - 0.061 LengthX s3
PosY	**1**	**21.2**	**0.04**	**0.1**	- 2.57 + 0.13 LengthY s3
	v	R^2	p	Cv	Regression Equation
Result	**3**	**35.1**	**0.07**	**3.3**	10.5 + 0.0188 Std10.0 s1 - 0.0105 Std10a0 s1 - 0.0818 LengthY s1
PosX	**2**	**21.6**	**0.13**	**1.4**	1.89 - 0.0397 Std10.0 s1 + 0.0273 Std10a0 s1
PosY	**1**	**9.1**	**0.20**	**0**	2.03 - 0.0152 Std10.0 s1
	v	R^2	p	Cv	Regression Equation
Std10.0 s5	**1**	**8.5**	**0.21**	**-0.6**	30.3 + 1.13 COPxLength s5
Std10a0 s5	**1**	**0.4**	**0.80**	**-1**	46.3 + 0.42 COPyLength s5
LengthX s5	**2**	**23.1**	**0.11**	**1.4**	56 - 1.76 COPxRange s5 + 7.49 COPyRange s5
LengthY s5	**3**	**49**	**0.01**	**3**	32.7 + 1.08 COPxLength s5 - 1.75 COPxRange s5 + 3.22 COPyRange s5
	v	R^2	p	Cv	Regression Equation
Std10.0 s3	**1**	**18**	**0.06**	**0.7**	74.8 - 6.7 COPxRange s3
Std10a0 s3	**1**	**21.6**	**0.04**	**-0.1**	99 - 24 COPyRange s3
LengthX s3	**1**	**20.4**	**0.05**	**-0.5**	23.1 + 1.6 COPyLength s3
LengthY s3	**1**	**23.5**	**0.03**	**-0.7**	20 + 5.39 COPyRange s3
	v	R^2	p	Cv	Regression Equation
Std10.0 s1	**4**	**62.8**	**0.00**	**5**	58.5 + 26 COPxLength s1 - 35 COPxRange s1 - 11.8 COPyLength s1 + 34.9 COPyRange s1
Std10a0 s1	**4**	**38**	**0.11**	**5**	77.2 + 17.2 COPxLength s1 - 12.5 COPxRange s1 - 15.2 COPyLength s1 + 22 COPyRange s1
LengthX s1	**2**	**39.1**	**0.02**	**2.2**	10.3 + 2.81 COPyLength s1 - 6.06 COPyRange s1
LengthY s1	**2**	**47.4**	**0.00**	**2.1**	4.03 + 1 COPxLength s1 + 3.06 COPyRange s1

R5

Table F.13: Correlation Matrix: Body sway data and shot result data for R5

	Result	PosX	PosY
COPxLength s5	**-0.26**	**0.16**	**0.19**
COPxRange s5	**-0.27**	**0.21**	**0.19**
COPyLength s5	**0.13**	**-0.16**	**-0.04**
COPyRange s5	**-0.11**	**-0.07**	**0.30**
COPxLength s3	**-0.39**	**0.08**	**0.51***
COPxRange s3	**-0.49***	**0.37**	**0.41**
COPyLength s3	**0.24**	**-0.26**	**-0.12**
COPyRange s3	**0.02**	**0.06**	**-0.01**
COPxLength s1	**-0.24**	**-0.10**	**0.48***
COPxRange s1	**-0.29**	**-0.05**	**0.52***
COPyLength s1	**0.15**	**-0.32**	**0.06**
COPyRange s1	**-0.03**	**-0.13**	**0.21**

Table F.14: Correlation Matrix: Aim point data and shot result data for R5

	Result	PosX	PosY
Std10.0 s5	**0.15**	**-0.11**	**-0.16**
Std10a0 s5	**-0.02**	**0.02**	**0.02**
Length s5	**-0.03**	**-0.03**	**0.09**
LengthX s5	**-0.10**	**-0.01**	**0.17**
LengthY s5	**0.07**	**-0.02**	**-0.04**
Std10.0 s3	**0.18**	**-0.03**	**-0.24**
Std10a0 s3	**0.27**	**-0.11**	**-0.26**
Length s3	**-0.06**	**0.00**	**0.09**
LengthX s3	**-0.13**	**0.07**	**0.14**
LengthY s3	**0.19**	**-0.18**	**-0.10**
Std10.0 s1	**0.21**	**0.04**	**-0.32**
Std10a0 s1	**0.31**	**-0.15**	**-0.30**
Length s1	**0.06**	**-0.20**	**0.03**
LengthX s1	**0.04**	**-0.09**	**-0.04**
LengthY s1	**0.09**	**-0.33**	**0.18**

Table F.15: Correlation Matrix: Aim point data and body sway data for R5

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s5	**-0.17**	**-0.14**	**-0.01**	**0.07**
Std10a0 s5	**-0.25**	**-0.20**	**-0.03**	**-0.08**
Length s5	**-0.15**	**-0.28**	**0.17**	**-0.27**
Length X s5	**-0.26**	**-0.37**	**-0.16**	**-0.44**
LengthY s5	**0.19**	**0.18**	**0.56****	**0.34**
Std10.0 s3	**-0.21**	**-0.28**	**0.09**	**-0.18**
Std10a0 s3	**-0.34**	**-0.37**	**-0.05**	**-0.16**
Length s3	**-0.25**	**-0.10**	**0.20**	**0.22**
Length X s3	**-0.31**	**-0.14**	**-0.04**	**0.00**
LengthY s3	**0.22**	**0.17**	**0.63****	**0.57****
Std10.0 s1	**-0.39**	**-0.37**	**-0.48***	**-0.47***
Std10a0 s1	**-0.21**	**-0.19**	**-0.43**	**-0.67****
Length s1	**0.03**	**-0.09**	**0.64****	**0.69***
LengthX s1	**-0.14**	**-0.23**	**0.46***	**0.54***
LengthY s1	**0.44**	**0.29**	**0.77****	**0.74****

Table F.16: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for R5

	v	R^2	p	Cv	Regression Equation
Result	**1**	**7.2**	**0.25**	**-0.1**	10.6 - 0.107 COPxRange s5
PosX	**1**	**4.5**	**0.37**	**-0.1**	0.696 + 0.171 COPxRange s5
PosY	**1**	**9.2**	**0.20**	**-0.1**	- 0.49 + 2.08 COPyRange s5
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**2**	**37.2**	**0.02**	**1.3**	10.3 - 0.33 COPxRange s3 + 0.124 COPyLength s3
PosX	**2**	**26.5**	**0.07**	**2.5**	1.3 + 0.531 COPxRange s3 - 0.246 COPyLength s3
PosY	**2**	**33.2**	**0.03**	**1.2**	- 0.24 + 0.354 COPxLength s3 - 0.203 COPyLength s3
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**1**	**8.3**	**0.22**	**0**	10.4 - 0.17 COPxRange s1
PosX	**2**	**15.9**	**0.23**	**1.3**	1.7 - 0.803 COPyLength s1 + 1.79 COPyRange s1
PosY	**1**	**26.7**	**0.02**	**-0.8**	0.419 + 0.668 COPxRange s1
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**1**	**2.1**	**0.54**	**0.2**	9.84 + 0.0056 Std10.0 s5
PosX	**1**	**1.1**	**0.54**	**-0.6**	9.84 + 0.0056 Std10.0 s5
PosY	**1**	**2.9**	**0.47**	**0.4**	- 0.48 + 0.027 LengthX s5
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**1**	**7.2**	**0.25**	**-0.1**	9.33 + 0.0111 Std10a0 s3
PosX	**1**	**3.4**	**0.44**	**-0.8**	2.71 - 0.0658 LengthY s3
PosY	**1**	**6.8**	**0.27**	**-0.2**	3.07 - 0.0237 Std10a0 s3
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**2**	**24.8**	**0.09**	**2.4**	7.01 + 0.0267 Std10a0 s1 + 0.071 LengthX s1
PosX	**3**	**30.6**	**0.11**	**3.1**	8.39 - 0.0508 Std10a0 s1 - 0.102 LengthX s1 - 0.206 LengthY s1
PosY	**2**	**24**	**0.10**	**1.3**	8.08 - 0.0573 Std10a0 s1 - 0.154 LengthX s1
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0 s5	**1**	**2.8**	**0.48**	**-0.8**	74.2 - 0.696 COPxLength s5
Std10a0 s5	**1**	**6**	**0.30**	**-0.9**	84.1 - 1.03 COPxLength s5
LengthX s5	**2**	**25.8**	**0.08**	**1.2**	79.2 - 1.43 COPxRange s5 - 15.6 COPyRange s5
LengthY s5	**1**	**30.9**	**0.01**	**-0.5**	2.7541 25 + 1.41 COPyLength s5
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0 s3	**1**	**7.6**	**0.24**	**0.5**	81.7 - 4.54 COPxRange s3
Std10a0 s3	**1**	**14**	**0.10**	**-0.6**	91.2 - 5.15 COPxRange s3
LengthX s3	**1**	**9.8**	**0.18**	**-0.7**	44.2 - 1.14 COPxLength s3
LengthY s3	**2**	**46.6**	**0.01**	**1.4**	14 + 0.857 COPyLength s3 + 5.33 COPyRange s3
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0 s1	**2**	**28.2**	**0.06**	**1**	99.4 - 5.89 COPxRange s1 - 32.5 COPyRange s1
Std10a0 s1	**2**	**48.8**	**0.00**	**1.1**	106 - 56.6 COPyRange s1 + 5.98 COPyLength s1
LengthX s1	**2**	**26.7**	**0.07**	**1.1**	9.77 - 0.731 COPxLength s1 + 2.43 COPyLength s1
LengthY s1	**2**	**62.3**	**0.00**	**1.9**	2.77 + 1.48 COPyLength s1 + 3.34 COPyRange s1

R6

Table F.17: Correlation Matrix: Body sway data and shot result data for R6

	Result	PosX	PosY
COPxLength s5	**0.02**	**0.24**	**-0.32**
COPxRange s5	**-0.12**	**0.36**	**-0.48***
COPyLength s5	**-0.07**	**0.06**	**-0.08**
COPyRange s5	**0.11**	**-0.22**	**0.01**
COPxLength s3	**0.12**	**0.13**	**-0.40**
COPxRange s3	**0.16**	**0.07**	**-0.47***
COPyLength s3	**-0.21**	**0.10**	**0.14**
COPyRange s3	**-0.18**	**0.01**	**0.19**
COPxLength s1	**-0.11**	**0.23**	**-0.07**
COPxRange s1	**-0.38**	**0.36**	**0.11**
COPyLength s1	**-0.19**	**0.21**	**-0.11**
COPyRange s1	**-0.39**	**0.34**	**0.07**

Table F.18: Correlation Matrix: Aim point data and shot result data for R6

	Result	PosX	PosY
Std10.0 s5	**0.17**	**-0.18**	**-0.03**
Std10a0 s5	**-0.19**	**0.22**	**0.14**
Length s5	**0.10**	**-0.27**	**0.07**
LengthX s5	**0.05**	**-0.10**	**-0.15**
LengthY s5	**0.19**	**-0.44**	**0.29**
Std10.0 s3	**0.17**	**-0.26**	**0.10**
Std10a0 s3	**0.17**	**-0.06**	**0.00**
Length s3	**0.05**	**-0.10**	**-0.05**
LengthX s3	**0.00**	**0.01**	**-0.20**
LengthY s3	**0.10**	**-0.28**	**0.28**
Std10.0 s1	**0.32**	**-0.28**	**-0.13**
Std10a0 s1	**0.12**	**0.29**	**-0.55***
Length s1	**0.05**	**-0.05**	**-0.08**
LengthX s1	**-0.07**	**0.13**	**-0.16**
LengthY s1	**0.24**	**-0.39**	**0.18**

Table F.19: Correlation Matrix: Aim point data and body sway data for R6

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s5	**0.20**	**0.25**	**-0.08**	**-0.09**
Std10a0 s5	**0.31**	**0.15**	**0.03**	**-0.38**
Length s5	**-0.28**	**-0.22**	**0.63****	**0.54***
LengthX s5	**-0.10**	**-0.02**	**0.54***	**0.42**
LengthY s5	**-0.42**	**-0.39**	**0.51***	**0.54***
Std10.0 s3	**-0.08**	**0.07**	**-0.29**	**-0.29**
Std10a0 s3	**0.20**	**0.16**	**-0.34**	**-0.20**
Length s3	**-0.22**	**-0.40**	**0.70****	**0.53***
LengthX s3	**-0.02**	**-0.09**	**0.48***	**0.35**
LengthY s3	**-0.43**	**-0.66****	**0.58****	**0.52***
Std10.0 s1	**0.20**	**0.01**	**0.04**	**-0.05**
Std10a0 s1	**0.17**	**0.26**	**-0.04**	**-0.16**
Length s1	**0.13**	**-0.40**	**0.09**	**0.03**
LengthX s1	**0.09**	**-0.39**	**0.24**	**0.22**
LengthY s1	**0.03**	**-0.24**	**-0.27**	**-0.35**

Table F.20: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for R6

	v	R^2	p	Cv	Regression Equation
Result	**2**	**6.5**	**0.57**	**1.3**	9.78 - 0.0707 COPyLength s5 + 0.946 COPyRange s5
PosX	**1**	**13.3**	**0.11**	**0.5**	- 0.12 + 0.607 COPxRange s5
PosY	**1**	**23**	**0.03**	**0.6**	3.33 - 0.624 COPxRange s5
	v	R^2	p	Cv	Regression Equation
Result	**1**	**4.3**	**0.38**	**-0.9**	10.6 - 0.0624 COPyLength s3
PosX	**1**	**1.7**	**0.68**	**-0.4**	- 0.92 + 0.243 COPxLength s3 + 0.147 COPyLength s3
PosY	**1**	**22.3**	**0.04**	**0.3**	2.45 - 0.472 COPxRange s3
	v	R^2	p	Cv	Regression Equation
Result	**3**	**34**	**0.08**	**3.2**	11.1 - 0.328 COPxRange s1 + 0.361 COPyLength s1 - 1.93 COPyRange s1
PosX	**2**	**22.7**	**0.11**	**1.2**	- 1.12 + 0.956 COPxRange s1 + 2.02 COPyRange s1
PosY	**2**	**12.6**	**0.32**	**1.5**	1.35 - 1.06 COPyLength s1 + 3.36 COPyRange s1
	v	R^2	p	Cv	Regression Equation
Result	**2**	**10.4**	**0.39**	**1.3**	10.4 + 0.00965 Std10.0 s5 - 0.0146 Std10a0 s5
PosX	**1**	**19.5**	**0.05**	**0.9**	6.83 - 0.122 LengthY s5
PosY	**2**	**15.1**	**0.25**	**2**	1.64 - 0.0564 LengthX s5 + 0.0818 LengthY s5
	v	R^2	p	Cv	Regression Equation
Result	**1**	**3**	**0.47**	**-0.1**	9.16 + 0.0105 Std10a0 s3
PosX	**2**	**17.8**	**0.46**	**1.2**	5.97 - 0.0177 Std10a0 s3 - 0.114 LengthY s3
PosY	**2**	**12.8**	**0.31**	**1.2**	1.17 - 0.0527 LengthX s3 + 0.0898 LengthY s3
	v	R^2	p	Cv	Regression Equation
Result	**1**	**10.2**	**0.17**	**0.7**	9.51 + 0.00626 Std10.0 s1
PosX	**1**	**15.5**	**0.09**	**2.2**	4.96 - 0.401 LengthY s1
PosY	**2**	**45.4**	**0.01**	**1.2**	12.5 - 0.092 Std10a0 s1 - 0.228 LengthX s1
	v	R^2	p	Cv	Regression Equation
Std10.0 s5	**1**	**6.2**	**0.29**	**-0.5**	44.3 + 4.59 COPxRange s5
Std10a0 s5	**2**	**34.5**	**0.03**	**1.3**	90 + 2.79 COPyLength s5 - 45.8 COPyRange s5
LengthX s5	**1**	**28.9**	**0.01**	**-1**	47.3 + 1.09 COPyLength s5
LengthY s5	**2**	**44.9**	**0.02**	**3**	39.5 - 0.69 COPxLength s5 - 1.81 COPxRange s5
	v	R^2	p	Cv	Regression Equation
Std10.0 s3	**1**	**3.7**	**0.42**	**0.3**	83.5 - 1.21 COPyLength s5
Std10a0 s3	**1**	**11.6**	**0.14**	**-0.5**	92.6 - 1.68 COPyLength s3
LengthX s3	**1**	**23.5**	**0.03**	**0.2**	26.1 + 1.3 COPyLength s3
LengthY s3	**2**	**50.4**	**0.00**	**1.1**	22.3 + 0.652 COPyLength s3 - 1.62 COPxRange s3
	v	R^2	p	Cv	Regression Equation
Std10.0 s1	**1**	**4**	**0.40**	**-0.1**	56 + 10 COPxLength s1
Std10a0 s1	**3**	**16.6**	**0.39**	**3**	92.1 + 5.61 COPxRange s1 + 6.27 COPyLength s1 - 24.5 COPyRange s1
LengthX s1	**3**	**39**	**0.04**	**3**	8.37 + 1.86 COPxLength s1 - 2.8 COPxRange s1 + 2.67 COPyRange s1
LengthY s1	**1**	**12.5**	**0.13**	**0.5**	9.96 - 2.21 COPyRange s1

P1

Table F.21: Correlation Matrix: Body sway data and shot result data for P1

	Result	PosX	PosY
COPxLength s1	**-0.52***	**0.52***	**0.17**
COPxRange s1	**-0.37**	**0.49***	**0.00**
COPyLength s1	**0.06**	**-0.01**	**-0.04**
COPyRange s1	**-0.01**	**-0.02**	**0.08**

Table F.22: Correlation Matrix: Aim point data and shot result data for P1

	Result	PosX	PosY
Std10.0 s1	**0.47***	**-0.22**	**-0.36**
Std10a0 s1	**0.49***	**-0.46***	**-0.25**
Length s1	**-0.47***	**0.33**	**0.28**
LengthX s1	**-0.39**	**0.24**	**0.27**
LengthY s1	**-0.33**	**0.34**	**0.12**

Table F.23: Correlation Matrix: Aim point data and body sway data for P1

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s1	**-0.47***	**-0.51***	**-0.19**	**-0.23**
Std10a0 s1	**-0.56***	**-0.43**	**-0.22**	**-0.28**
Length s1	**0.43**	**0.27**	**0.06**	**0.11**
LengthX s1	**0.38**	**0.37**	**0.04**	**0.10**
LengthY s1	**0.22**	**-0.07**	**0.04**	**0.04**

Table F.24: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for P1

	v	R^2	p	Cv	Regression Equation
Result	**3**	**45.8***	**0.02**	**3**	10.8 - 0.475 COPxLength - 0.962 COPyLength - 1.46 COPyRange
PosX	**2**	**34.2***	**0.03**	**1.5**	-2.83 + 2.68 COPxLength - 1.42 COPyLength
PosY	**3**	**19.7**	**0.31**	**3.4**	5.15 + 1.5 COPxLength - 7.83 COPyLength + 15 COPyRange
	v	R^2	p	Cv	Regression Equation
Result	**2**	**29.9***	**0.05**	**2.2**	10.6 + 0.0207 Std10.0 - 0.0253 LengthX
PosX	**1**	**21.1***	**0.04**	**-0.2**	17.3 - 0.162 Std10a0
PosY	**1**	**13.2**	**0.26**	**0.2**	5.6 + 0.0184 Std10.0
	v	R^2	p	Cv	Regression Equation
Std10.0	**1**	**25.7***	**0.02**	**1.2**	73 - 18.1 COPxRange
Std10a0	**3**	**40.1***	**0.04**	**3.2**	67.7 + 6.1 COPxLength - 6.88 COPxRange - 13.8 COPyLength + 31.8 COPyRange
LengthX	**3**	**22.8**	**0.33**	**3.5**	61.6 + 2.52 COPxLength + 2.7 COPxRange - 8.53 COPyLength + 15.6 COPyRange
LengthY	**3**	**15.3**	**0.43**	**3**	46.6 + 3.74 COPxLength + 3.09 COPxRange

P2

Table F.25: Correlation Matrix: Body sway data and shot result data for P2

	Result	PosX	PosY
COPxLength s1	**-0.35**	**-0.10**	**-0.08**
COPxRange s1	**-0.23**	**-0.16**	**0.00**
COPyLength s1	**0.03**	**0.00**	**-0.30**
COPyRange s1	**0.02**	**-0.06**	**-0.11**

Table F.26: Correlation Matrix: Aim point data and shot result data for P2

	Result	PosX	PosY
Std10.0 s1	**0.39**	**-0.16**	**-0.36**
Std10a0 s1	**0.02**	**-0.02**	**0.06**
Length s1	**-0.06**	**0.08**	**-0.06**
LengthX s1	**-0.01**	**0.13**	**-0.11**
LengthY s1	**-0.15**	**0.05**	**0.05**

Table F.27: Correlation Matrix: Aim point data and body sway data for P2

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s1	**0.05**	**0.11**	**0.00**	**-0.11**
Std10a0 s1	**-0.01**	**-0.04**	**-0.06**	**0.03**
Length s1	**0.00**	**-0.03**	**0.18**	**-0.04**
LengthX s1	**-0.01**	**0.03**	**0.31**	**0.21**
LengthY s1	**0.09**	**-0.04**	**-0.11**	**-0.39**

Table F.28: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for P2

	v	R^2	p	Cv	Regression Equation
Result	**2**	**14.4**	**0.27**	**1.2**	9.37 - 0.255 COPxLength + 0.105 COPxRange
PosX	**2**	**14**	**0.28**	**1.3**	1.34 + 0.918 COPxLength + 0.94 COPyLength
PosY	**2**	**5**	**0.65**	**1.4**	5.08 + 0.782 COPxLength - 0.97 COPyLength
	v	**R^2**	**p**	**Cv**	Regression Equation
Result	**3**	**23.7**	**0.22**	**2.1**	9.54 + 0.00923 Std10.0 + 0.0107 LengthX - 0.0137 LengthY
PosX	**1**	**2.5**	**0.51**	**0.7**	6.82 - 0.0198 Std10.0
PosY	**2**	**24.1**	**0.10**	**1.5**	17.8 - 0.0911 Std10.0 - 0.113 LengthX
	v	**R^2**	**p**	**Cv**	Regression Equation
Std10.0	**1**	**7.8**	**0.71**	**3.8**	73 - 18.1 COPxRange
Std10a0	**3**	**3.2**	**0.93**	**3.3**	67.7 + 6.1 COPxLength - 6.88 COPxRange - 13.8 COPyLength
LengthX	**2**	**10.4**	**0.39**	**1.7**	61.6 + 2.52 COPxLength + 2.7 COPxRange
LengthY	**2**	**27.9**	**0.06**	**2.1**	46.6 + 3.74 COPxLength + 3.09 COPxRange

P3

Table F.29: Correlation Matrix: Body sway data and shot result data for P3

	Result	PosX	PosY
COPxLength s1	**0.11**	**-0.08**	**-0.10**
COPxRange s1	**0.04**	**0.07**	**-0.08**
COPyLength s1	**-0.01**	**-0.44**	**0.34**
COPyRange s1	**-0.01**	**-0.36**	**0.24**

Table F.30: Correlation Matrix: Aim point data and shot result data for P3

	Result	PosX	PosY
Std10.0 s1	**0.63****	**-0.40**	**-0.51***
Std10a0 s1	**0.18**	**-0.01**	**-0.18**
Length s1	**-0.14**	**-0.18**	**0.36**
LengthX s1	**-0.07**	**-0.18**	**0.22**
LengthY s1	**-0.27**	**-0.06**	**0.47***

Table F.31: Correlation Matrix: Aim point data and body sway data for P3

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s1	**-0.32**	**-0.44**	**0.06**	**0.06**
Std10a0 s1	**-0.62****	**-0.52***	**-0.21**	**-0.03**
Length s1	**0.60****	**0.45***	**0.28**	**0.05**
LengthX s1	**0.49***	**0.35**	**0.30**	**0.13**
LengthY s1	**0.43**	**0.42**	**0.04**	**-0.15**

Table F.32: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for P3

	v	R^2	p	Cv	Regression Equation
Result	**2**	**1.3**	**0.90**	**1.1**	9.37 - 0.255 COPxLength + 0.105 COPxRange
PosX	**1**	**19**	**0.06**	**-0.6**	9.25 - 1.41 COPyLength
PosY	**1**	**11.7**	**0.14**	**-0.5**	0.36 + 1.68 COPyLength
	v	R^2	p	Cv	Regression Equation
Result	**2**	**53****	**0.002**	**1.1**	10.1 + 0.0226 Std10.0 - 0.0181 Std10a0
PosX	**3**	**35.6**	**0.06**	**3.4**	21.9 - 0.09 Std10.0 - 0.101 LengthX - 0.09 LengthY
PosY	**4**	**47.8***	**0.04**	**5**	- 24.6 - 0.133 Std10.0 + 0.212 Std10a0 + 0.132 LengthX + 0.217 LengthY
	v	R^2	p	Cv	Regression Equation
Std10.0	**1**	**19.2***	**0.05**	**-0.7**	73 - 18.1 COPxRange
Std10a0	**4**	**43.8***	**0.01**	**1.5**	67.7 + 6.1 COPxLength - 6.88 COPxRange - 13.8 COPyLength + 31.8 COPyRange
LengthX	**4**	**35.2***	**0.03**	**1**	61.6 + 2.52 COPxLength + 2.7 COPxRange - 8.53 COPyLength + 15.6 COPyRange
LengthY	**2**	**20.5**	**0.14**	**1.8**	46.6 + 3.74 COPxLength + 3.09 COPxRange

P4

Table F.33: Correlation Matrix: Body sway data and shot result data for P4

	Result	PosX	PosY
COPxLength s1	**0.20**	**-0.09**	**-0.21**
COPxRange s1	**0.15**	**0.01**	**-0.27**
COPyLength s1	**-0.23**	**0.16**	**0.16**
COPyRange s1	**-0.34**	**0.28**	**0.20**

Table F.34: Correlation Matrix: Aim point data and shot result data for P4

	Result	PosX	PosY
Std10.0 s1	**0.07**	**-0.21**	**0.19**
Std10a0 s1	**0.10**	**0.12**	**-0.30**
Length s1	**-0.04**	**-0.05**	**0.12**
LengthX s1	**0.00**	**0.00**	**0.07**
LengthY s1	**-0.04**	**-0.09**	**0.13**

Table F.35: Correlation Matrix: Aim point data and body sway data for P4

	COPxLength	COPxRange	COPyLength	COPyRange
Std10.0 s1	**-0.28**	**-0.21**	**0.24**	**0.11**
Std10a0 s1	**-0.24**	**0.20**	**0.13**	**0.04**
Length s1	**0.04**	**0.03**	**-0.53***	**-0.49***
LengthX s1	**-0.02**	**-0.10**	**-0.62****	**-0.55***
LengthY s1	**0.09**	**0.13**	**-0.34**	**-0.36**

Table F.36: Best multiple regression equations for the prediction of shooting performance from body sway, shooting performnce from aim point fluctuation and aim point fluctuation from body sway for P4

	v	R^2	p	Cv	Regression Equation
Result	**2**	**18.6**	**0.17**	**1.9**	9.37 - 0.255 COPxLength + 0.105 COPxRange
PosX	**3**	**16.8**	**0.39**	**3.4**	0.74 COPxLength - 5.17 COPyLength + 12.6 COPyRange
PosY	**2**	**12.2**	**0.33**	**1.3**	1.83 COPxRange + 4.2 COPyRange
	v	R^2	p	Cv	Regression Equation
Result	**2**	**1.2**	**0.90**	**1**	0.0046 Std10a0 + 0.00157 LengthX
PosX	**2**	**8.2**	**0.48**	**1.4**	0.0711 Std10.0 + 0.0507 Std10a0
PosY	**2**	**18**	**0.32**	**1.5**	0.11 Std10.0 - 0.128 Std10a0
	v	R^2	p	Cv	Regression Equation
Std10.0	**1**	**15.7**	**0.23**	**2.2**	73 - 18.1 COPxRange
Std10a0	**4**	**61.6***	**0.004**	**5**	67.7 + 6.1 COPxLength - 6.88 COPxRange - 13.8 COPyLength + 31.8 COPyRange
LengthX	**3**	**44.4***	**0.02**	**3.1**	61.6 + 2.52 COPxLength + 2.7 COPxRange - 8.53 COPyLength + 15.6 COPyRange
LengthY	**4**	**15.8**	**0.60**	**5**	46.6 + 3.74 COPxLength + 3.09 COPxRange