A Multidisciplinary Analysis of Handballing in Australian Rules Football

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Abstract

Skilled sports performance demands technical and perceptual-cognitive expertise. A true understanding of any one skill requires an examination of both factors. This thesis aimed to determine the biomechanical and perceptual-motor underpinnings of the Australian football handball through the use of performance analysis, biomechanics and motor learning. A novel performance analysis system assessed 12 in-game technical, decision-making and environmental factors of handball executions. Each factor was coded in detail using between two and six category levels. The application of this system revealed that efficiency was higher when players were square, passing forward and in a knees-bent or running stance, and lower when players were under higher pressure, had fewer passing options available, were positioned in the offensive zone, and after indirectly receiving the ball. Performance analysis directed the choice of skill execution and biomechanical parameters for the subsequent three studies. The next stage of this thesis used three-dimensional biomechanics to analyse handballing technique for speed and accuracy with preferred and non-preferred hands. Factors identified as influential for performance included shoulder and elbow joint motion and hand path. The preferred-arm movement pattern involved greater use of the trunk and arm. Canonical correlation evaluated the combined factors of speed and accuracy identifying a parameter of importance (elbow range), which was not evident when speed and accuracy were analysed independently. Building on the biomechanical knowledge, the thesis then proceeded to understanding the perceptual-motor components of the skill, using two studies. This was achieved with a novel 360° stimulus-response task, which manipulated task complexity using both auditory and visual stimuli. Overall, the two studies showed kinematic and response time differences between stimulus modalities and between levels of cognitive complexity. A highlight of this thesis is the use of three sports-science disciplines, which included performance analysis, biomechanics and motor learning. The work provides contributions to each discipline, and illustrates the value of a multidisciplinary approach. Specifically, the design of this programme of study and its phased use of disciplines provides a framework for future work that similarly attempts to deliver a comprehensive evaluation of skill. The outcome of this approach is the high quality of applicable information for testing and training of the skill.

Student Declaration

I, Lucy Jane Victoria Parrington, declare that the PhD thesis entitled A multidisciplinary analysis of handballing in Australian Football is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature Date

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List of Publications and Awards

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Awards

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1 General Introduction

1.1 A multidisciplinary approach

Team sport is a domain in which there is an inextricable link between biomechanical and perceptual-cognitive aspects of performance. Team sports skills require an athlete to quickly perceive and interpret the game environment and proceed with an effective decision while performing with technical precision (Jackson & Beilock, 2008). The ability to choose the best option in a particular game scenario and to execute the skill with precision is essential for elite sports performers. For example, the utility of a player who has technical efficiency when passing, but continually passes the ball to the opposition due to ineffective processing of cognitive information is limited. A player who can make the correct decision but is unable to carry out the decision due to technically flawed performance is limited in a similar way. Starkes, Cullen, and MacMahon (2004) refer to this as the link between perceptual-cognitive and perceptual-motor skills, explaining that the level of ability in one may either facilitate or constrain the other.

Sports science research has been conducted typically with focus placed upon performance from either a technical (biomechanical) or a cognitive (decision making processes – e.g. anticipation, perception, visual search) perspective. For example, the focus of many biomechanical studies has been related to the kinematics and/or kinetics of discrete closed skills (e.g. skills which have a more defined beginning and end point, Magill, 2007). The closed skill and controlled environment may help isolate movement requirements to address technical cues, or aid in providing evidence-based coaching cues, however this may not address some critical factors present in an actual game situation. Comparatively, motor learning research with a focus on decision making may not consider the fact that a good theoretical decision maker may suffer during game play if they are inefficient at processing *in-situ*, or if they possess a technical deficiency. Ultimately, these disciplinary approaches are required in isolation, as well as in combination with each other, in order to allow a complete picture of the skill to be developed.

Through the use of novel designs, previous research has provided abundant empirical evidence, about the technical or cognitive aspects that guide skilful performance. Yet, few studies have taken a combined approach that uses the results of one field to guide and direct exploration of the same skill from another research discipline. This research attempts to address biomechanical and perceptual-motor factors pertaining to handballing in Australian football players, by analysing both performance and outcome parameters using an approach, which builds across multiple disciplines - including performance analysis, biomechanics and motor learning. Application of a multidisciplinary approach, as such, has the potential to provide a more in-depth, and thoroughly considered, understanding of the one skill.

1.1.1 Australian football as an example of a complex sport

Australian football is a high profile sport nationally, in which the elements of expert performance can be examined. It provides an excellent example of a dynamic environment that involves various levels of constraints and continually changing conditions. It is Australia's leading spectator sport (Australian Bureau of Statistics, 2010) and is one of the most popular participation sports from a recreational level through to professional ranks (Australian Football League, 2013a).

Australian football requires players to have a high level of perceptual and technical ability. It is an invasion game involving a number of layers of complexity. One example involves the use of an oval ground, which affords multi-directional play. It is a full-contact sport, which increases the implications of a player being tackled because of physical contact. This, in particular, places players under temporal constraints, as there is a penalty for holding onto the ball when tackled. Therefore, players benefit from the ability to read and react in a timely fashion in order to pass the ball prior to contact from an opposition player. Teams also benefit from accuracy, as scoring within the inner section of the goal area is worth six points, whilst the outer area (on either side of the inner section) is worth only one point.

Competent technical abilities are integral to the performance of all sport skills (Hughes & Bartlett, 2002) and the ovoid shape of the football adds further complexity to the technical performance of Australian football motor skills. Complications that exist relate to the nature of impact (Ball, 2011a) between the ground, foot and hand, because different points of the football's circumference are at different distances from the ball's geometric centre. Consequently, this requires precision during contact to avoid unpredictable ball flight and bounce properties, which can complicate anticipation of the football's direction and increase the perceptual demand of players.

The combined application of performance analysis, biomechanics and motor learning disciplines can be used to gain a greater depth of understanding of the technical and perceptual-cognitive complexities involved in Australian football. This method, although focussed specifically on Australian football, has great potential to extend transferrable skills and generalisable information to other games or activities that share similar perceptual elements (Thorndike & Woodworth, 1901).

1.1.2 The Australian football handball as an example of a complex skill

Handballing in Australian football is one of two methods of legally passing the ball between players (ball disposal). It involves holding the football in one hand and striking it with the other hand using a clenched fist. The number of handballs per team per game has increased 42% between 1999 and 2012 and now makes up almost half

(43% - 47%) of all passes (Australian Football League, 2012). Handballing has become an increasingly fundamental skill within Australian football due to its high effectiveness in maintaining ball possession. Handballing efficiency is approximately 20% higher than kicking efficiency (Champion Data, 2012). The rate of success of handballing is despite the fact that the majority of handballs, in comparison with kicks, have been shown to occur in contested situations (Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004a). The effectiveness of handballing in games is an outcome of both technical and cognitive expertise, and therefore contributes to the rationale of using this task as an example skill in which both of these aspects can be analysed.

Despite the increased use of handballing within Australian football, there is a lack of information on this fundamental skill. The absence of scientific literature on handballing provides a perfect starting position for a multidisciplinary study. There is a lack of information and understanding of the factors that influence handballing efficiency during elite competition games. This gap can be addressed through performance analysis. Only general coaching literature is available on the mechanics of handballing. Although this information provides a starting point for understanding the handball, this coaching information is provided without empirical evidence of the biomechanics involved. Kinematic analysis can provide an understanding of the technical mechanisms by which the handball is performed. Finally, the context in which the handball is used within the game (i.e. close to ball contest, Dawson et al., 2004a) emphasises that timely and effective perception and response is required in order to address various environmental constraints placed upon Australian footballers.

1.1.3 Gaps in the biomechanics literature

In their review of performance indicators in sport, Hughes and Bartlett (2002) referred to ‘skill’ as the most pertinent requirement for the success of any athlete.

Bartlett indicated further that there is a lack of biomechanical analysis in team sports. The study of biomechanical indicators in sport can provide knowledge of the general framework of the movement pattern. In this approach, the assessment of an elite sample of players is a common practice used to develop a greater understanding of the technical elements involved in performance (Hughes & Bartlett, 2002). Empirical evidence from assessing the biomechanics of a skill is a pre-cursor for the construction of practice drills and sessions that can further be developed through collaboration with motor learning theorists and coaches (Davids, Lees, & Burwitz, 2000; Elliot, 2006). Furthermore, biomechanical knowledge aids the evaluation and provision of coaching cues and can help direct feedback to players (Buttfield, Ball, & MacMahon, 2009).

Prior to this research, biomechanical studies in Australian football have been limited to kicking. Ball (2008) identified technical factors associated with distance kicking. Ball found that the speed of the striking segment contacting the football was positively correlated with both ball speed and projectile distance in maximal Australian football kicking. In addition, Ball found a continuum of kicking styles among elite players, indicating that not all players use the same technique, yet are still able to achieve similar distances.

The kinematic differences between accurate and inaccurate groups of drop-punt kickers have also been evaluated (Dichiera et al., 2006). Greater anterior pelvic tilt at heel contact, hip flexion in both legs and greater knee flexion in the support-leg knee throughout the kicking movement were evident in the more accurate kicking group. Researchers suggested that the increased joint flexion was used a method of increasing stability in the movement.

In addition to the findings about general kicking styles, performance decrements and kinematic differences in the non-preferred limb have been documented (Smith, Ball, & MacMahon, 2009; Ball, 2011b). Ball (2011b) found a different movement pattern between preferred and non-preferred kicks. It was suggested that this might be related to Bernstein's (1967) theory of the freezing of degrees of freedom in the less developed, non-preferred limb.

Other examples of kicking research include investigations of the foot-to-ball interaction (Smith et al., 2009), studies of muscle function during kicking (Orchard, Walt, McIntosh, & Garlick, 2001; Orchard, McIntosh, Landeo, Savage, & Beatty, 2003), kicking and footedness research (Cameron & Adams, 2003), kinematics of kicking under fatigue (Coventry et al., 2011) and a study of the coordination profiles of elite kickers (Falloon, Ball, MacMahon, & Taylor, 2010).

Although biomechanics literature in Australian football has focussed predominantly on kicking performance, Hughes and Bartlett (2002) suggested that performance indicators are generally applicable across a number of different sports skills. Therefore, whilst no scientific literature has been available specific to the Australian football handball, previous biomechanics literature on drop punt kicking has provided direction in relation to parameters that may be of interest, and appropriate statistical methods that can be utilised in order to analyse these parameters.

1.1.4 Gaps in the motor-learning literature

In contrast to the beliefs of Hughes and Bartlett (2002), many consider perceptual-cognitive ability as one of the key differentiations between expert and novice athletes and thus a key component to the outcome of dynamic sport competitions (Abernethy, 1987; Williams, Davids, Burwitz, & Williams, 1992). The ability to address pertinent cues within the game environment, interpret this information, and then quickly and accurately select an appropriate response from the alternative options is undoubtedly an essential skill set for any competitive athlete (Baker, Côte, & Abernethy, 2003; Farrow & Raab, 2008).

Specifically, early studies have documented empirical evidence on the differences between novice and expert performers, such as the superiority of experts' perceptual cognitive ability over that of their novice counterparts (e.g. pattern recognition and recall, Allard, Graham, & Paarsalu, 1980; Starkes, 1987; anticipation, Abernethy, 1990; Abernethy & Russell, 1987). Research methodologies have developed from the use of static slide representations (e.g. Bard & Fleury, 1976; Starkes, 1987) and video displays (e.g. Royal et al., 2006), to three-dimensional projected displays (Ranganathan & Carlton, 2007) and more recently, simulated game activities (e.g. Bruce, Farrow, Raynor, & Mann, 2012; Mann, Abernethy, & Farrow, 2010). The different methods in which research has been conducted has allowed researchers to study different components of athletes' anticipation, perceptual and decision-making ability. Moreover, researchers have used particular paradigms to extract information on different components of the skill in order to gain a better understanding of the mechanisms underpinning skilled performance.

Recent motor learning research in Australian football has focused on the use of video-based decision making assessment. For example, Berry, Abernethy, and Côte (2008) demonstrated the ability of video-based assessment of decision making to discriminate between elite and less-skilled decision-makers. The results from the video-based decision making test were compared against the rankings of Australian football coaches. Ranks from both of these methods demonstrated a high level of agreement, showing that the video-based method used was able to capture decision-making ability quite well. Though expert decision-makers were found to outperform less-skilled decision-makers, Berry et al. (2008) did not provide information on the mechanisms that differentiate between groups, nor how this translates into on-field play.

In comparison with Berry et al. (2008), a collection of research conducted by Lorains and colleagues tested whether the presentation of different video speeds affected performance and if it discriminated between levels of participants (Lorains & MacMahon, 2009; Lorains, MacMahon, Ball, & Mahoney, 2011; Lorains, Ball, & MacMahon, 2013a; Lorains, Ball, & MacMahon, 2013b). Lorains and colleagues focussed on the testing experience through the use of above real time simulation of video-based decision-making testing and training. Specifically, ‘above real time’ simulation is believed to increase the feeling of time-pressure. Lorains et al. (2013a) demonstrated that elite participants performed more accurately as video speed increased, while sub-elite and novice participants declined in performance. In this study, athletes rated video that was 1.5 times the normal video speed as most ‘game-like’ and the authors suggested that this might present a more representative feeling of game conditions for decision making. As a result, the authors have proposed that above real time simulation is useful as a complementary video-based decision-making testing and training tool.

In-situ methodologies have been used to increase the sensory experience and perception of the testing environment (Mann, Williams, Ward, & Janelle, 2007). These methods have been implemented in an effort to understand how undertaking the movement contributes to task performance (Bruce, et al., 2012; Mann et al., 2010; Martell & Vickers, 2004; Müller & Abernethy, 2006; Müller et al., 2009; Panchuk & Vickers, 2006; Shim, Carlton, Chow, & Chae, 2005; Vickers & Williams, 2007). These coupled perception-action studies have been shown to provide a more complex and therefore naturalistic response compared with the use of verbal methods alone (e.g.

coupled and uncoupled responses in tennis, Farrow & Abernethy, 2003; Mann et al., 2010). Still, these studies may be limited by the following factors: (a) a focus on cognitive ability or overall outcome of performance, (b) a focus on visual stimuli, and (c) a focus on frontally presented stimuli. These factors limit the ability to gain a practical understanding of sensory information usage, or how perceptual constraints may affect technical performance.

Few researchers have observed how physical behaviour is affected by cognitive factors with any level of precision. In one of the few, a recent study by Panchuk, Davids, Sakadjian, MacMahon and Parrington (2013) examined the eye-movements and hand kinematics of participants catching tennis balls that were projected from a screen display. The apparatus featured video of a throwing action that was either coupled or decoupled with the ball trajectory. This study demonstrated poorer performance, later onset of ball tracking, less tracking of ball trajectory, later movement initiation and faster hand velocities in the absence of perceptual information. Another example of a simultaneous capture of different components of performance is the table tennis study conducted by Raab, Masters, and Maxwell (2005). This study analysed the kinematics of table tennis forehand shots during low and high complexity tests to address the implicit motor learning hypothesis. Despite using different complexity tests, kinematic results were only provided for pre- and post- learning conditions and not for task complexity. The methods used in Panchuk et al. and Raab et al. provide an interesting foundation for further protocol development where kinematic measures are used to aid motor-learning research.

There is limited sports science based research that has considered acoustic stimuli. This is despite the fact that during game play, stimuli may be detected acoustically as well as visually and that it may occur in myriad combined conditions to the left, right, or even behind a participant. In addition, responses to these two sources of information are known to be different, yet the contribution of auditory signals to perception appears to have been neglected in motor learning research.

The paucity of literature on acoustic influence may be an outcome of the robust findings of the 'Colavita' visual dominance effect, which refers to the dominance of visual over auditory responses to bimodal targets in human participants (Colavita, 1974). Based on the visual dominance effect, it may be hypothesised, that in the presence of visual stimuli, auditory information would not be beneficial. What is not accounted for with this rationale is the fact that there are many sporting situations where visual and acoustic information are not presented from the same target at the same time. This is important given findings that spatiotemporal factors influence the magnitude of the visual dominance effect (Koppen & Spence, 2007a; 2007b).

There are laboratory-based studies that indicate acoustic information may influence perceptual motor skills in complex game situations. For example, studies have found that head-eye responses to auditory stimuli are typically faster than responses to visual stimuli (Goossens & Van Opstal, 1997; Sanders, 1998). Furthermore, auditory signals have the ability to capture attention regardless of visual focus (Petocz, Keller, & Stevens, 2008; Szalma et al. 2004) and the ability to distract from other stimuli (Langendijk, Kistler, & Wightman, 2001). It is plausible therefore, that auditory signals may provide additional or different information in a sports setting, and present meaningful stimuli to assist in the decision-making process. This has not been addressed in previous sports decision-making studies. It is of interest, whether perceptual-motor skill differs in response to auditory in comparison with visual stimulus capture, and what, if any differences occur.

1.2 Orientation to the thesis

This thesis takes an in-depth multidisciplinary approach to analysis of skill in sport, using the Australian football handball as an example. The collaborative approach combines performance analysis, biomechanics and motor learning disciplines to guide analysis.

Study 1 (Chapter 2) establishes a profile of handball executions within game, as well as information on the percentage of effective and ineffective handballs during game play that may be attributed to either technical errors or decision-making flaws. By showing that both of these components are present during game-play and share a relationship with the outcome of the skill execution, Chapter 2 also provides the foundation for the need for research on both technical and tactical components of performance.

As a technical approach is recognised as an important stepping-stone to understanding game skills, the next three chapters (Chapters 3 – 5) take a comprehensive and systematic look at the technical aspects of the Australian football handball. Speed/ distance, accuracy and bilateral ability were each determined to be critical passing components, therefore each of these were assessed. First, Chapter 3 (Study 2) establishes descriptive kinematic data and identifies kinematic parameters associated with maximal handball speed performance using the preferred-hand. Chapter 4 (Study 3) assessed important kinematic differences between handballs performed using the preferred in comparison with the non-preferred arm. The last of the biomechanically focussed chapters, Chapter 5 (Study 4), looks at handballing on the preferred hand using a multifaceted statistical approach that considered within-group (accurate versus inaccurate handballers), within-individual (successful versus unsuccessful) accuracy performance, as well as a multivariate statistical analysis to understand the important factors when both accuracy and speed are required.

With the profile of handball executions during game play provided from Study 1 and a thorough evaluation of the biomechanical considerations of the handball covered in Studies 2, 3 and 4, Chapter 6 (Study 5) moves away from the kinematics and assesses handball performance under changes in cognitive load and stimulus type. This chapter is noteworthy because of the novel methodology used. The design linked perception and action in response to both auditory and visual cues, as well as testing in a 360-degree movement environment. Thus, participants were required to 'read and react' during the testing protocol to both sources of information occurring from multiple directions. This study observes stimulus-driven attention capture within a sports setting and introduces auditory information as an important contributor to decision-making research.

Chapter 7 (Study 6), the final study conducted, connects and ties the preceding chapters together. Using the kinematic parameters that were established as important in Studies 2 through 4, Chapter 7 addresses the effect that cognitive loading (task complexity) and the type of stimuli (environmental condition) have on handball technique. This chapter draws the connection between whether different perceptual task difficulty affects the technical performance of a skill in order to gain a greater understanding of elite player performance.

Chapter 8 provides an overview and general discussion of the research and thesis as a whole, taking a combined look at the results from the studies from each discipline and discussing the theoretical context that governs them. Practical considerations for coaches and researchers are provided, as well as recommendations for future research.

Conclusions are provided and discussed in Chapter 9 in order to reiterate the findings of the thesis. Additional information regarding biomechanical procedures has been provided in the Appendices.

1.3 Justification of the studies

A multidisciplinary approach has recently been called for in its role in contributing to both biomechanics and skill acquisition/ motor learning in sport (Buttfield et al., 2009). The independent assessment of skills from different research disciplines is noteworthy and a necessary process. An approach, which crosses multiple disciplines independently and collaboratively, may provide a greater depth of knowledge on skilled performance. Moreover, the analysis of skilled performance in a sport setting can contribute to other areas of cognitive research where task performance and decision making are inextricably linked (e.g. military combat situations, Janelle & Hatfield, 2008).

Examining the mechanical features of expert performance can provide an appropriate starting point in understanding how complex coordination of movement occurs (Davids et al., 2000). These data, though helpful for technical coaches, do not provide information on any benefit or detriment that occurs in the context of cognitive situations that are abundant on the playing field. Conversely, although there is a large base of literature on cognitive skills (Williams, Davids, & Williams, 1999), there is little empirical knowledge from coupled environments about mechanical changes, that is, how the movement is affected by changes to the perceptual environment (c.f. Panchuk et al., 2013; Raab et al., 2005).

During Australian football, the challenges and uncertainties faced by players, including the response that is required prior to movement execution, are common across other sports and other domains. Handball passes are used frequently in Australian football and are more effective than kicks in maintaining ball possession. However, prior to studies conducted throughout this thesis, there has been no focus on this skill within Australian football research. Similarly, there is little information pertaining to the cognitive aspects of game skills in Australian football.

Therefore, this research proposes to address the performance of the Australian football handball from an interdisciplinary approach in order to answer questions in a holistic manner, encompassing game analysis, biomechanical analysis and decision making considerations. The study intends to provide valuable evidence-based information to Australian football sporting bodies ranging from junior coaching and development, through to school programs and extending up to elite performance programs and professional AFL teams. This research assesses the effects of increasing task complexity on perceptual-motor skill, using a novel stimulus-response test and detailed kinematic analysis to collectively assess skilled performance. In addition, data collected in both visual and auditory settings aims to provide information on the response to different stimulus presentations, extending visual attention and auditory stimulus perception literature into the sport domain (e.g. Yao & Peck, 1997, Langendijk, et al., 2001). Research regarding the Australian football handball throughout this thesis represents an example skill analysed using a multidisciplinary approach, with this information applicable to a variety of different domains, both sporting and non-sporting in nature (e.g. driving or fire-fighting).

1.4 General aims

The aims of this thesis are to:

1. Profile the Australian football handball as it is used in elite competition and assess how technical, decision-making and environmental or lead-up conditions relate to a successful outcome in the Australian Football League.
2. Identify kinematics important for handballing in maximal and accuracy conditions, as well as differences for preferred and non-preferred hand.
3. Using handballing as the skill, identify whether perceptual-motor performance changed as an outcome of cognitive complexity or stimulus modality.

Specific aims for each study are provided within the associated chapter.

2 Study 1: Game-based handball analysis of handballing in Australian football

(Adapted from: Parrington, L., Ball, K., & MacMahon, C. (2013b). Game-based analysis of handball in Australian football. *International Journal of Performance Analysis in Sport*, *13*(3), 759-772.)

Handballing is the most efficient passing skill in Australian football with an 80% success rate. Other than the number and outcome of handballs, there is no game-based information available on handball quality. The aims of this study were to profile handball performance and to assess within-game factors associated with effective handballing. Handballs (*N* = 1140) from 14 Australian Football League games were coded for outcome, technical, decision-making and game-environment factors. Technically it was found that that most handballs during games were characterised by a stationary and square stance, and executed forward over a short distance. Decision-making components included passing under low pressure, within one and three seconds and with one to two passing options available. Under game-environment, handballs were predominantly made in the midfield and after the ball was caught in the air, with an 'easy-receive' lead-up. Efficiency was higher when the player was square, passed forward, and had a 'knees-bent' or running stance. Handballing efficiency was lower under increased pressure, when there were fewer passing options, in the attacking region of the ground, and after awkwardly receiving the ball before passing. These findings can help guide handball technical analyses and coaching programs.

2.1 Introduction

Australian football is an invasion game, where successful ball transfer between players about the field is a component of effective team performance. In Australian football the ball is passed between players (termed 'disposal') via a kick or handball. Kicks are performed either after releasing the ball from the hand, or by kicking it off the ground. The handball involves holding or cradling the ball in one hand and striking it with the fist of the other hand to propel the ball in a desired direction. Handballs are used less frequently than kicks (approximate disposals: 43% handballs vs. 57% kicks, Australian Football League, 2012) but are the more efficient method of passing (handball efficiency 80%, kicking efficiency 60%, Champion Data, 2012). The term 'efficiency' in Australian football refers to the percentage of passes made that are successful in maintaining possession.

Current performance analysis research in Australian football has focussed on time-motion assessment to define player movement patterns (e.g. Dawson et al., 2004a; Dawson, Hopkinson, Appleby, Stewart, & Roberts, 2004b) and physiologically classify player positions (Pyne, Gardner, Sheehan, & Hopkins, 2006; Veale, Pearce, & Carlson, 2007). For example, Veale et al. (2007) explored player movement patterns of different positions in elite juniors by quantifying the number of efforts (working vs. resting) and the distance covered for these efforts. Using similar procedures, Dawson et al. (2004a; 2004b) assessed movement patterns (walk, run, sprint, etc.) and game activities (bumps, tackles, disposals, etc.) in both games and training sessions across one AFL season.

Although previous research has provided detail on the different type and frequency of movements in Australian football, it has not assessed the indices of team or individual player performance of a skill (i.e. performance analysis, Hughes & Bartlett, 2002). Official league statistics (i.e. Champion Data) do provide data on the total number of skill executions, efficiency and provide the total number of passes made directly to the opposition ('clanger'). However, these game statistics do not provide contextual information on the skill, nor detail whether success or errors were due to technical, decision-making or game-environment factors. There is no literature detailing handball performance during Australian football games. In addition, the connection between the performance of handballs and factors that contribute to their outcome has not yet been assessed.

Providing more detail on each skill execution allows for profiling predominant technique(s) employed, conditions in which they are performed and efficiency factors, which can assist both coaching and scientific studies. This information allows coaches to adopt an evidence-based approach to training and team assessment on a number of levels. First, it can assist in the construction of technical practice drills that match the most common handball conditions (Hughes & Bartlett, 2002). That is, knowledge of what factors affect passing efficiency can help guide the skill content of training such that sessions consider which technical, tactical and decision-making components require work. Second, it can assist the evaluation of both team and individual strengths and weaknesses (Ball & Horgan, 2013). Finally, it can help coaches to assess the transfer effectiveness of training interventions focussed on technical errors. For example, this process was used by Ball (2005) to evaluate in-game set shot percentage success. The identification of the common skill executions and the conditions under which they occur is also beneficial from a research perspective. Skill-focused game-analysis can help guide subsequent biomechanical evaluation to appropriately account for the conditions under which a skill is performed (Ball & Horgan, 2013).

The purpose of this study was to profile handball executions and compare effective and ineffective handballs in Australian football, examining technical, decision-making and game-environment factors.

2.2 Method

Analysis was conducted using video footage from official network broadcasting of games from the 2008 and 2009 AFL pre-season cup and regular season competitions. Evaluations of approximately 1140 handballs were made across (a) the first quarter of six different teams, (b) the first quarter of one team across six games of the 2008 and 2009 seasons, whose club focus was improving handballing, and (c) across each quarter of one team for three games at the beginning of the 2009 season. This selection of handballs provided assessment across both different time periods and across six AFL teams to avoid distorted profiling (Hughes & Bartlett, 2002), providing group data that is generalisable to the AFL population.

Each handball was categorised considering four areas: outcome (efficiency and outcome type), technical factors (stance/ motion during handball, pass direction and distance), decision-making factors (pressure level, number of passing options, time to disposal) and game-environment factors (position on ground, ball height and direction prior to receiving ball and making pass; Table 2.1). Each parameter within these headings was identified and defined with the assistance of two professional Australian football coaches currently involved in coaching at the AFL level. Coding analysts were each trained and practiced in the parameter definitions prior to coding handballs. Analysts were unlimited in the number of replays of each handball execution to ensure accurate evaluation. Intra-rater and inter-rater reliability were calculated using Cohen's Kappa scores. Intra-rater reliability of the primary analyst was assessed by the evaluation and re-evaluation of one quarter (32 handballs), completed 24 hours apart. Two additional coding analysts were then trained and assessed against the primary analyst on a subset of 20 handballs. Both intra-rater and inter-rater reliability were classified as showing good agreement and above (above 0.61, Altman, 1991). All handball occurrences were coded and recorded into an Excel document.

Table 2.1

Handball profile definitions

		Parameter	Definition
Outcome measures	**1**	Efficiency	The success of the pass based on whether ball possession was maintained (efficient) or if there was a turn-over (inefficient)
	2	Outcome type	Break down of efficiency categorised by a clean pass (handball received without needing to change stride/ pre-pass movement); wayward pass (handball received but pass was difficult to catch causing a break in the flow of movement); in dispute win (handball dropped and regained or pass to free space where possession is maintained); in dispute loss (handball dropped or a pass to free space where the opposition gains possession); marked player (handball made to a teammate who is clearly marked); or clanger (handball made direct to opposition)
Technical factors	**3**	Player stance	Square position where line between left and right hip is perpendicular to the line of motion of the ball (e.g. hips are open and facing the target).
	4	Player stance/ motion	The position of the player and whether the player was in-motion or stationary
	5	Pass direction	Direction that the ball was passed in relation to the player's shoulder line
	6	Pass distance	The distance that the handball was passed over, categorised as short (6 m or less) and long (greater than 6 m)
Decision making factors	**7**	Pressure	High: Tackled during handball Moderate: Opposition within 5 m and influences decision (Tackle imminent) Low: Opposition within 5 m and do not influence decision None: Opposition outside of 5 m and does not influence decision
	8	Number of pass options	Number of available players in support of the ball carrier
	9	Time to dispose ball	Time the player is in possession of the ball prior to making the pass
Game-environment factors	**10**	Position on ground	Position from which the handball was made with the ground divided into three sections. The inside-50 areas are determined by the team that was coded in a particular game (i.e. the defensive or attacking ends of the field for the team of interest)
	11	Receiving ball height	The height that the ball was received by the player prior to the handball that was made. Either caught in the air or picked up from a ground ball, where the ball had bounced first. Ground balls were subdivided below and above knee heights.
	12	Ball direction	The direction that the ball was moving prior to the player receiving the ball and making the handball pass. Categorised as easy (ball is moving directly toward the player when received), hard (ball is moving indirectly away from the player when received), or other (ball picked up from ground contests)

Each parameter was normalised against the total frequency of handballs (Hughes & Bartlett, 2002). Expressing data as percentages or proportions (e.g. turn-overs as a percentage of possessions) is advocated to facilitate comparisons and to provide more detail to researchers and coaches (Nevill, Atkinson, Hughes, & Cooper, 2002). To examine how the coded factors might influence efficiency, a percentage of efficiency (%E) was calculated for each parameter. This was the number of handballs that were successful (e.g. square to target and successful), calculated as a proportion of the total number of times that parameter category occurred (e.g. number of handballs where players were square). Hughes and Bartlett (2002) recommend this method to aid interpretation of data. To reduce confusion with data given for profile information, the percentage of efficiency is written as %E.

2.3 Results

Intra-rater reliability was very good for eight parameters and good (above 0.61) and thus acceptable for the remaining four. Inter-rater reliability was very good for 10 parameters and good and acceptable (above 0.61) for the remaining two (Table 2.2).

Table 2.2

Intra-rater and inter-rater reliability

Parameter	**Intra-rater Cohen's Kappa**	**Inter-rater Cohen's Kappa**
Outcome measures		
Efficiency	1.00	1.00
Outcome type	0.85	0.86
Technical factors		
Squaring up	0.81	0.87
Stance/ motion	0.79	0.78
Pass direction	0.92	0.91
Pass distance	0.91	0.95
Decision making factors		
Pressure	0.79	0.87
Number of options	0.72	0.65
Time to disposal	0.81	0.85
Game-environment factors		
Ground position	1.00	1.00
Ball height	0.77	0.83
Ball direction	0.86	0.83

Overall, handballing efficiency was 84%. Handball profile data and percentage of efficiency data for technical, decision making and game-environment factors are presented in Table 2.3.

Table 2.3

Handball profile and percentage of efficiency data

Parameter				**%**	**% E**
Outcome measures	**1**	Efficiency	Efficient	84%	
			Inefficient	16%	
	2	Outcome type	Clean pass	65%	
			Wayward pass	11%	
			In dispute win	8%	
			In dispute loss	8%	
			Marked player	4%	
			Clanger	4%	
Technical factors	**3**	Player stance	Squared	64%	91%E
			Not squared	36%	70%E
	4	Player stance/ motion	In-motion (run or jog)	44%	88%E
			Stationary – upright	25%	80%E
			Stationary – knees bent	22%	88%E
			Stationary – on ground	9%	67%E
	5	Pass direction	Forward	76%	88%E
			Across body	22%	71%E
			Backward/ Behind	2%	54%E
	6	Pass distance	Short	78%	84%E
			Long	22%	85%E
Decision making factors	**7**	Pressure	High	25%	64%E
			Moderate	21%	84%E
			Low	44%	92%E
			None	10%	98%E
	8	Number of pass options	None	2%	21%E
			One or two	72%	85%E
			Three or more	26%	87%E
	9	Time to dispose ball	Less than 1s	40%	84%E
			1s < time < 3s	52%	83%E
			3 or more s	8%	85%E
Game-environment factors	**10**	Position on ground	Defensive 50	21%	91%E
			Midfield	68%	83%E
			Offensive 50	11%	72%E
	11	Receiving ball height	Caught in air	60%	89%E
			Below knee pick-up	25%	76%E
			Above knee pick-up	15%	77%E
	12	Ball direction	Easy-receive	70%	86%E
			Hard-receive	17%	78%E
			Other	13%	79%E

Among technical factors, efficiency differed for stance positions. Efficiency was 21%E lower when the player was not square, in comparison with being square to their pass. Having the knees bent or hand passing while in-motion (running/ jogging) were equally the most efficient stance positions. Efficiency was 8%E lower when players were standing upright (without knees bent) and 21%E lower for passes made from the ground. Passes made across the body were 17%E less efficient than passes made forward, and handballs backward/ behind the body or over the shoulder were the least efficient. Pass distance varied by 1%E between short and long passes. For the decision-making factors, success decreased when pressure increased. Efficiency was approximately 65%E lower when no passing options existed in comparison with either one-two, or three or more options, and efficiency was within 2%E for all categories of time to dispose ball. For the game-environment factors, the highest efficiency occurred in the defensive 50, while passes in the forward 50 were the least efficient. Passing efficiency was highest after the ball had been received in the air with an easy-receive. Efficiency was lower after ground balls, but the difference between an above and below knee pick-up of a ground ball was only 1%E.

2.4 Discussion

2.4.1 Profile of handballs

Efficiency of handballing in this study (84%) was similar to that reported by Champion data (2012) in AFL games (80%). As well, the percentage of 'clangers' (handballs made directly to the opposition) was equivalent to previously reported statistics (4%, Champion Data, 2012). There are no other data for comparison within the literature. Seventy-seven percent of effective passes were well executed and made direct to a teammate, allowing the receiver to maintain stride. Thirteen-percent caused the receiver to alter their actions to receive the ball. This may have been due to a technical error or a misjudged point of target; for example, where a player has made a good decision of the player to whom to pass and performed the handball with good technique, but misjudged the position of the moving receiver. The remaining 10% of efficient handballs were from passes dropped or made into free space that were regained.

For handballs categorised as in-dispute after being dropped or passed into free-space, possession was regained 50% of the time. Of the ineffective passes, 25% were due to being passed to a marked player, 25% due to clangers and 50% were in-dispute losses. Both passes to marked players and clangers were attributed to either a technical or decision-making error. For example, where a player made a correct decision, but a technical error caused the ball to go to someone else, or where good technique was used, but there was a poor choice of target. In-dispute losses were credited to either technical or decision errors on the part of either the passer or the receiver.

Technically, handballs were most commonly characterised as stationary and square to the passing target, executing a short pass in the forward direction. Handballs were performed more from a stationary position rather than when in-motion. However, it should be noted that the stationary passes were further subdivided and that in-motion passes as a category of stance position occurred more than any of the subdivision categories of stationary stance position. Of the stationary subdivisions, standing upright (tall, knees extended) occurred the most (45%), followed by a ‘knees-bent’ stance (39%). Handballs performed from the ground occurred the least of all the stationary stance handballs (16%).

The most common decision-making components accompanying handballs included handballing under low pressure, within one to three seconds of receiving the ball, and with one or two passing options available. Examining pressure in more detail, though low pressure situations occurred most often of the four levels measured, 46% of passes were performed under moderate or high pressure. Dawson et al. (2004a) reported that for most player positions, handballs were performed under a contested situation. Both the skill level of players, and the definition of moderate and high pressure in this study and classification of contested situation pressure were similar in this study to those in Dawson et al. (2004a). Therefore, we compared the findings, using the mean and range values to calculate the percentage of contested versus uncontested handballs as an average across the player positions assessed. The results of this study indicate a lower percentage of moderate/high-pressure handballs in contrast to the percentage of contested handballs across player positions, using both the mean (61%) and range (55%) values reported by Dawson et al. (2004a). The discrepancy between findings may be due to differences in interpretation of definitions, although both indicated that moderate/high pressure were situations in which there was either a tackle or tackle imminent. Another cause for the difference in results between the two studies may be the different samples used. Playing an aggressive team that tackles or bumps often results in more contested situations and possibly a higher percentage of contested handballs. Understanding how aggressive a team is leading into competition may aid coaching directives in training prior to a game.

Notably, 54% of handballs were performed without influence of the opposition, yet 92% of handballs were made within three s of receiving the ball. This finding might suggest that players are attempting to move or pass the ball quickly regardless of external influence. This might indicate that players take advantage of the speed of this type of disposal in order to catch the opposition “off-guard”, a tactic suggested by McLeod and Jaques (2006).

Among game-environment factors, handballs were performed predominantly in the midfield after the ball was caught in the air in an easy-receive lead-up direction, where the ball was moving toward the receiving player when it was caught. Due to the oval shape of the Australian football field, the midfield has a greater total area compared with other sections (inside 50), and is likely to have influenced this finding. Additionally, there is more time spent in play in the midfield (58%) than in the defensive and forward 50 (21% each; Champion Data, 2012). The smaller percentage of handballs in the forward 50 in comparison with the defensive 50 may be a result of players attempting to kick for goal rather than handball. Previous biomechanical analysis of elite Australian football players found the maximal kick distance to be 68m (Ball, 2008). Therefore, there is potential for players to attempt a kick for goal without needing to pass within the forward 50. In addition, if players wish to gain a set shot attempt at goal (after 'taking a mark') then it is a better game strategy to pass via kick in this area. Finally, handballs occurred after being caught in the air and after an easy-receive.

2.4.2 Percentage of efficiency

Technically, the most efficient handballs were executed when players were square to their receiver, passing forward, and either in-motion (jogging/ running) or in a 'knees-bent' stance if stationary. This is in agreement with Parrington et al.'s (2012) biomechanical case study (n = 4), which examined pelvis position at ball contact. Parrington et al. (2012) found a link between more square position and handballing accuracy. Results of this study provide game-based evidence in support of Parrington et al.'s findings and that pelvic position is a technical parameter that contributed to technical performance. A knees-bent stance might provide a more balanced position from which to handball and move towards a target. Kinematic evaluation is suggested to aid the understanding of why a knees-bent stance was more efficient than an upright stance in games.

Efficiency was affected by the pass direction. In particular, compared with forward passes, efficiency was 17% lower when passes were made across the body. This finding is in line with Parrington et al. (2012) who found that accuracy of forward passes decreased when the strike-path of the hand at ball contact was angled in relation to the target (i.e. swung across the line direct to the target centre). Passing across the body may affect the strike path of the hand toward the intended target. Passing across the body also decreases the likelihood of having a squared posture. Therefore, a drop in efficiency for across the body passes compared with forward passes could be influenced by both stance and/or strike-path.

The change in efficiency between the different stationary body positions (knees-bent, 88%E, upright, 80%E) is of technical interest. The knees-bent stance may be beneficial in assisting balance or ball momentum. Firstly, bending the knees provides a lower body centre of mass, which may potentially assist the dynamic stability of the player. Secondly, having the knees bent could be linked with a wider or longer stance position that allows the 'transfer of weight' from the back foot to the front and may therefore help to transfer momentum to the ball (Knudson, 2007). This transfer of momentum is similar to taking a step forward, which has been suggested to assist with ball flight velocity or distance (McLeod & Jaques, 2006).

Pass distance did not influence the success of passes, with efficiency for short and long handballs within 1% of each other, indicating that players are able to use both short and long passes efficiently. The definition of distance used in this analysis may not have been sufficient to compare efficiency. Measuring this factor within game may be aided with the knowledge of the maximum pass distance in an elite sample. Potential handball distance is limited in comparison with kick distance because of the striking speed of the segment in contact with the ball (foot-speed 26.4 m/s, Ball, 2008, hand speed 10.4 m/s, Parrington, Ball, MacMahon, & Taylor, 2009) and some players may choose to pass using a kick, rather than trying to handball beyond their capabilities.

When efficiency was compared based on decision-making factors, the comparison showed that handball efficiency was highest when there was no pressure and when there were players in support of the ball carrier. Results indicated that handballing efficiency decreased as pressure increased. These findings are in agreement with Bruce, Farrow, Raynor, and May (2009), who reported a smaller percentage of successful passes under high defensive pressure in comparison with low defensive pressure situations in netball. Bruce et al. (2009) suggested changes in passing technique as a possible link between increased passing errors and the higher levels of pressure. Results of this study indicate that technical factors are adversely affected by physical pressure, with a higher percentage of 'not-squared' passes made under conditions of moderate and high pressure (Figure 2.1). The 21% decrease in efficiency for not-squared passes implies that technical elements may contribute to the link between decreased success and higher pressure.

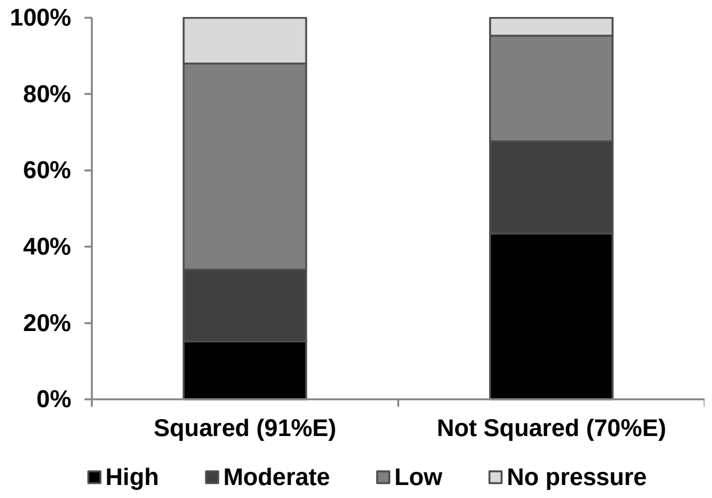


Figure 2.1: Percentage of pressure for squared and not squared stance.

Efficiency was not influenced by disposal time (range 83-85%E). This indicates that players were able to make successful passes when they were time constrained to the same extent as when they had longer to perceive the environment. Notably, pressure influenced both disposal time and efficiency, but disposal time did not influence efficiency. To explain, a decrease in disposal time was accompanied by a greater percentage of high and moderate pressure, yet efficiency stayed within 2% across disposal time categories (Figure 2.2). Under shorter time intervals, elite Australian footballers are proposed to use a more automated decision response (Lorains et al., 2013a), which may result in a successful outcome. On the other hand, longer disposal times allowing more time to collect information from the environment, could result in equally effective decisions and passes.

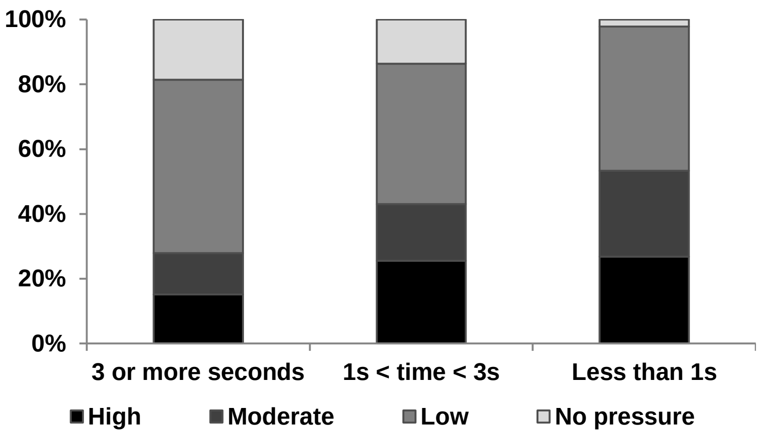


Figure 2.2: Percentage of pressure for disposal time categories.

In order to further explain why time to dispose was quicker under pressure, but did not affect efficiency, the number of successful passes made under moderate/high pressure was calculated *post-hoc* for each disposal time (Table 2.4). Under moderate and high pressure, more successful passes occurred in less than one s, than ‘between one and three seconds’ and ‘more than three seconds’.

Table 2.4

Percentage of successful passes made under moderate and high pressure

Disposal time	Percentage
Less than 1s	40%
1s < time < 3s	31%
3 or more s	19%

Bruce et al. (2009) speculated that taking additional time to pass might result in passing errors because time constraints for ball movement may result in less time to execute the skill. Netball has a three s time constraint to move the ball, to which Australian football is not subjected; however, players who take additional time when under moderate or high-pressure may be trying to break free to make the handball and this additional constraint may result in a less effective pass. Extrapolated from this line or argument, physical pressure may influence both technical and decision-making factors. Information pertaining to the execution of skill and decision-making may be an influential factor to analyse and a meaningful contribution to the literature. Thus, the extent to which the magnitude of physical pressure affects decision-making capabilities and the technical ability of players when handballing requires further investigation.

Although it is logical that having no passing options leads to a drop in efficiency, the data from this study point out the benefits of unobstructed teammate support. Of interest may be that supporting players in addition to one-two options did not greatly change efficiency (2% increase when three or more players available). This finding is in contrast to the results of Bruce et al. (2009), who found more successful passes when fewer options were present. An increase in player support above two valid options is potentially redundant because players may not even see or consider all of the possible alternatives (Raab & Johnson, 2007). Therefore, it is possible that efficiency found for three or more passing options is not markedly greater than when only one or two options are present because players are likely to take the first meaningful option, regardless of the number of available players.

Game-environment factors had an impact on handballing efficiency. The most successful conditions involved hand-passes made in the defensive 50 and when the lead-up involved the ball being caught in the air and easy-receives. In comparison with the defensive 50, there was an 8% and 19% decrease in efficiency in the midfield and forward 50, respectively. The difference in efficiency by ground area could be linked to pressure, with only 14% handballs made in the defensive 50 compared with 26% in midfield and 42% in the forward 50 under high pressure. Further, only 2% of handballs made in the forward 50 were executed under no pressure, while 10% and 13% were registered in the midfield and defensive 50. This supposition was assessed *post-hoc*, with Pearson's chi-square test revealing an association between position on ground and pressure on the ball carrier ($\chi^2(6) = 45.49$, $p < 0.001$). The percentage of pressure per ground position is presented in Figure 2.3. Pressure was found to adversely affect efficiency (e.g. an approximate 30% decrease in efficiency under high pressure in comparison with low pressure).

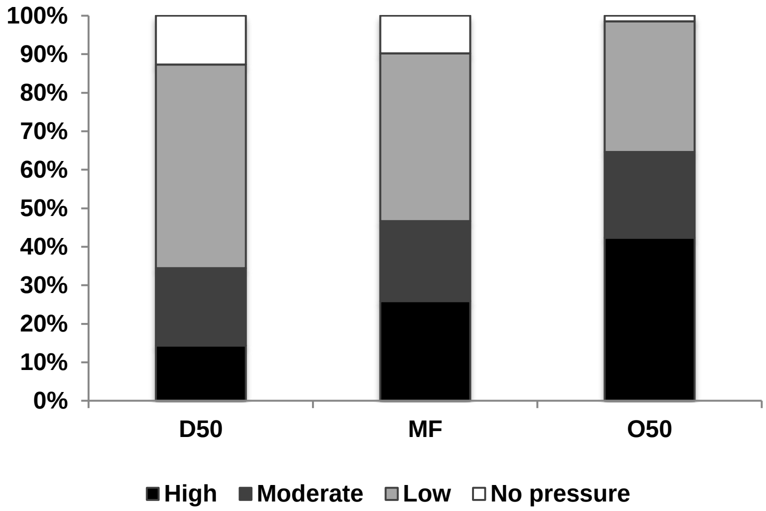


Figure 2.3: Percentage of pressure for ground position.

The efficiency results for lead-up demonstrated that the quality of the pass that precedes each handball is influential in the outcome of the pass that follows. The efficiency for both ground ball conditions was lower than for those caught in the air, although the height at which the ball was received after it had bounced from the ground did not appear to play a role. Similarly, efficiency was lower when the ball had been moving away from the player or required a pick up from ground-contest. Reduced efficiency may be explained by increased contest for the ball or reduced attention devoted to environmental cues. For example, ground ball pick-ups occurred under tackle (high pressure) more than when the ball was caught in the air (15%), for both below-knee pick-ups (44%) and above-knee pick-ups (33%). This was similar for ball direction with hard-receives and pick-ups from ground contests occurring under tackle more than easy-receives (41%, 31% and 20%, respectively). Therefore it is plausible that a lower efficiency occurred in these lead-up conditions due to players being restricted by tackle. Another explanation is that more predictable ball flight lends itself to anticipation of ball reception, thus allowing for more attention to environmental cues prior to the handball pass that follows. Therefore, the lower efficiency found for handballs from ground or hard-receives may be associated with a need to place more focus on gaining control of the ball, rather than having the chance to observe and read the play.

2.4.3 Implications for coaching and research

The identification of a game-specific profile of handballs and the game demands associated with their execution during elite match play has a number of applications for coaches and researchers. Firstly, data facilitates the adoption of an evidence-based approach to the construction of practice (Hughes & Bartlett, 2002). Use of handball profile data can suggest conditions for handball performance. For example, handball drills should occur under at least low-level pressure to match common game conditions. An understanding of the factors that affect passing efficiency can also help guide the skill content of training by identifying areas that require work. Since efficiency drops as pressure increases, it is vital that handballs occur more often in practice under contested situations. Dawson et al. (2004b) found that only 5% of handballs during practice involved physical pressure. Our data suggest high and moderate pressure together occurs close to 50% of the time. An increase of the number of contested handballs in practice from 5% is thus recommended.

Coaches may not advocate full physical contests during training because of injury risks. Implied physical pressure can achieve the same goal, and be accomplished by players running at the ball carrier, or by incorporating touch tackling. Another example of how efficiency information can be used is that handballs were less effective after ground ball lead-up conditions. Practice involving ground balls and varying the lead-up ball direction may help players react to these conditions better in games.

From a research perspective, the information provided can help drive skill evaluation. For example, this study found higher efficiency in forward directed handballs characterised by a squared running or knees-bent stance in comparison with other stance positions and pass directions. Evaluation on how these technical factors and other biomechanical factors influence the handball may be useful. In addition, pressure affected efficiency and disposal time, but disposal time did not affect efficiency. This suggests that it may be worthwhile to examine technical changes in response to pressure and decision-making scenarios.

Amendments to rules, improved conditioning and developments in player skill and decision-making as well as tactical trends in coaching may have the potential to change the profile of particular skills such as handballing. Therefore, a follow up study on the next most recent AFL season is a viable future research consideration.

2.5 Conclusion

This study characterised handballs in elite Australian football games. Common technique involved a squared, stationary stance and short passes to the front, rather than across the body, while the most common decision-making components included handballing under low pressure, within one and three seconds of receiving the ball and when there were one or two passing options available. For game-environment, handballs occurred most in the midfield and involved a lead-up where the ball was caught in the air after it had been travelling toward the player. Efficiency was highest when players were square, passing forwards and either in-motion (jogging/running) or using a ‘knees-bent’ stance if stationary. Handballs were more efficient under decreased levels of pressure and when there were players in support of the ball carrier. Handballs were most efficient in the defensive 50 and when the lead-up involved the ball being caught in the air or in an easy-receive. Training can be improved by replicating game demands. Therefore, technically, players should focus on being square to their pass, passing forward rather than across their body, and if stationary, on having a good knees-bent stance. Coaches should implement handballing training drills that simulate moderate and high pressure situations and factor in ground ball conditions where the ball is received after bouncing at varying heights. Finally, coaches should also implement drills, which prompt practice handballs after hard-receives, where the ball is moving away from the player.

3 Study 2: Biomechanical characteristics of handballing maximally in Australian football

(Adapted from: Parrington, L., Ball, K., & MacMahon, C. (In Press). Biomechanical characteristics of handballing maximally in Australian football. *Sports Biomechanics.*)

The handball pass is influential in Australian football and achieving higher ball speeds in flight is an advantage in increasing distance and in reducing the chance of interceptions. The aim of this study was to provide descriptive kinematic data and identify key technical aspects of maximal speed handball performance. Optotrak Certus collected three-dimensional upper and lower body data from 19 professional Australian football players performing handballs for maximal speed. Hand speed at ball contact was used to determine performance. Sixty-four kinematic parameters were initially calculated using Visual3D, then were reduced using a two-stage supervised principal components analysis procedure to 15, which were used to describe the kinematics of the handball. The second stage involved grouping the 15 parameters into like components to facilitate regression analysis. Multiple regression analysis indicated that greater hand speed was associated with greater shoulder angular velocity and separation angle between the shoulders and pelvis at ball contact, as well as an earlier time of maximum upper-trunk rotation velocity. These data suggest that to increase hand speed, increasing shoulder angular velocity, separation angle at ball contact and achieving earlier upper trunk rotation speed might be beneficial.

3.1 Introduction

Australian football is Australia’s leading spectator sport (Australian Bureau of Statistics, 2010). Legal movement of the ball between players (disposal) is performed through either kicking or handballing. Handballing involves holding the ball in one hand and punching it with the clenched fist of the other hand to propel it to an intended target (Figure 3.1). Handballs contributed to approximately 43% of all disposals in 2012, in comparison with only 35% in 1999. Since 1999 the average number of kicks per team per game has only increased from 194 to 205 (6% increase), while the average number of handballs made per team per game has increased from 106 to 151 (42% increase). These game statistics suggest that ball disposal has increased over this period predominantly through the use of handballing at a rate of almost four handballs to one kick (Australian Football League, 2012).

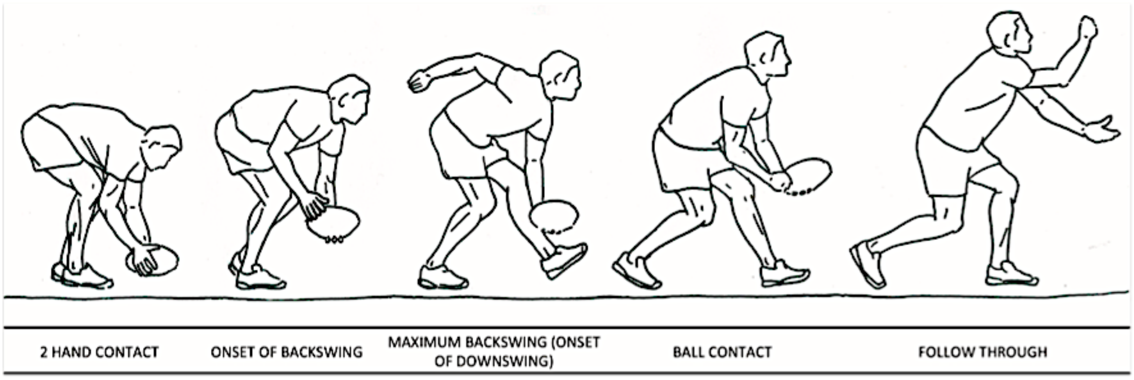


Figure 3.1: Handball sequence.

Handballing has been described within coaching as a ‘potent weapon’ that allows quick movement and effective continuation of play (McLeod & Jaques, 2006). Game statistics from the 2012 AFL grand final (Champion Data, 2012) reinforce its effectiveness in maintaining possession, with handballing efficiency (80%) much higher than kicking efficiency (60%). In addition, handballs are less likely to be erroneously passed directly to the opposition (handball clanger) in comparison with kicks (4% vs. 11% of total disposals).

In spite of this increased emphasis on and importance of the handball in the game of Australian football, little scientific literature exists on the technical elements that contribute to handball performance. Hughes and Bartlett (2002) suggested that performance indicators generally transcend across different sports. Kinematic sequencing (Putnam, 1993) and movement variables may be shared with other underarm sports skills like softball windmill pitching (Barrentine, Fleisig, Whiteside, Escamilla, & Andrews, 1998; Werner, Guido, McNeice, Richardson, & Stewart, 2005; Werner, Jones, Guido, & Brunet, 2006) and tennis forehand ground shots (Landlinger, Lindinger, Stoggl, Wagner, & Muller, 2010). In exclusion of the handball, biomechanics studies in Australian football have predominantly focussed on kicking (e.g. distance kicking, Ball, 2008; preferred and non-preferred foot kicking, Ball, 2011b; accuracy, Dichiera et al. 2006; footedness, Cameron & Adams, 2003; and muscular activity, Orchard et al., 2001). Of importance here given this study is examining a maximal task, the speed of the striking segment contacting the football was positively correlated with both ball speed and projectile distance in maximal Australian football kicking (Ball, 2008).

In one of the only previous studies on the handball, Parrington, Ball, MacMahon, and Taylor (2009) performed a case study on one elite Australian football player to gain a preliminary understanding of the technical elements of the handball. This study found that hand speed, linear shoulder speed, shoulder angular velocity and elbow angular velocity at ball contact were greater in a maximal speed handball condition compared with an accuracy condition. The large effect sizes found in the study suggest that these parameters are appropriate for more in depth research on the area. Parrington and colleagues (Parrington, Ball, & MacMahon, 2012) also looked at a small sample (*n* = 4) of elite players to establish variables associated with coaching cues, while discriminating between accurate and inaccurate passes. Accurate passes were characterised by slower hand speed, slower humeral angular velocity, lower upper arm and elbow range of motion (ROM), and a more square pelvis orientation, and a larger upper arm angle at ball contact. As well, the hand path of the striking hand was directed more toward the target in accurate handballs. Given both studies collected data on small samples (n = 1 and n = 4), this information can be used as a guide, but may not be generalisable to the broader Australian football population. However, the effect sizes found in Parrington, Ball, MacMahon, and Taylor (2009) and Parrington et al. (2012) suggested technical differences exist and are thus worthy of further exploration in a larger sample to assess this generalisability.

Studying the biomechanical parameters that relate to the performance of a skill in an elite sample of players is common practice to develop a greater understanding of the technical elements involved in successfully producing that skill (Hughes & Bartlett, 2002). This can provide an appropriate starting point in understanding how complex coordination of movement occurs (Davids et al., 2000). In collaboration with motor learning theorists and coaches, knowledge of the general framework of the movement pattern is an important step in the construction of practice drills and sessions (Elliot, 2006). In addition, this knowledge can assist the evaluation and provision of coaching cues, and can help direct feedback to players (Buttfield et al., 2009). Therefore, the aims of this study were, (a) to provide descriptive kinematic data on handballing from elite Australian footballers, and (b) to identify important kinematic parameters associated with handball performance through supervised principal component analysis and regression analysis.

3.2 Methods

3.2.1 Participants

Nineteen elite and sub-elite professional male Australian football players (19 ± 1.5 years, 1.9 ± 0.1 m, 84.6 ± 7.8 kg, 16 right-hand preferred, 3 left-hand preferred) currently playing or completing pre-season training participated in this study. The Human Research Ethics Committee of Victoria University approved the use of human subjects. Written consent was provided from each subject before data collection.

3.2.2 Procedure

Participants wore standard training apparel (compression tights or shorts, t-shirt or singlet, and running shoes) during testing. Rigid body clusters composed of three non-collinear active makers each were placed on the torso (neck and pelvis), and bilateral upper (upper arm, forearm and hand) and lower extremities (shank and thigh) to create an interlinked biomechanical model. Elasticised neoprene wrap and sports tape was used to help secure the clusters. An additional marker was placed on the base of the fifth metatarsal to assess step length.

After marker attachment and digitisation of anatomical landmarks, participants completed an easy paced (50-70% effort) five minute cycle or jog, followed by at least five handballs on the preferred hand to become familiar with the equipment and surroundings. To help simulate a game situation, the testing procedure required players to catch the football at mid-chest height and perform a handball with maximal effort toward a target that sat 5m in front of the testing area. The ball delivery that preceded the handball was made with back-spin, at approximately 1.5 metres and at a 90 degree angle from the line between the participant and the target.

A catching net was in place mid-way between the target and the testing area. The centre of the target was positioned at a height of 1.5m and in line with the Y-axis of the global reference system of the lab (see Figure 3.2, also Appendix F). For testing, participants were instructed to perform the handball with maximal effort (for maximum speed) toward the target beyond the net. Five good trials were taken, with participant self-reported atypical trials repeated. Good trials were defined as handballs that felt correct or consistent ,whilst atypical trials were those that felt uncharacteristic to the participant. All testing was completed using a standard football (Sherrin, official competition ball, inflated pressure range 62-76 kPa).

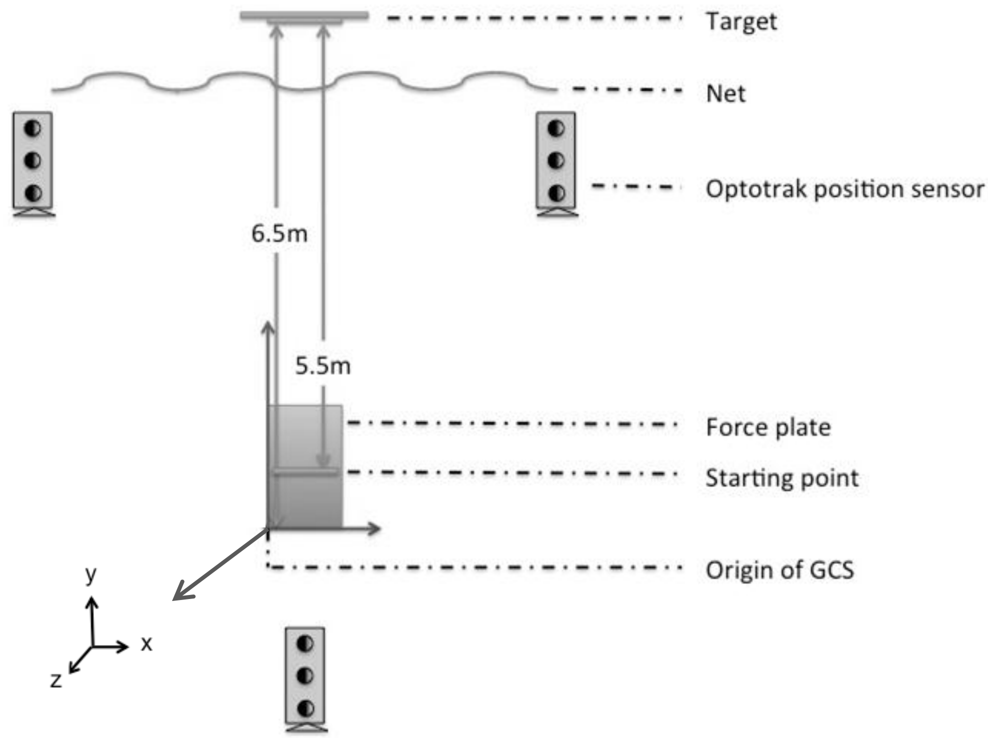


Figure 3.2: Laboratory diagram and global coordinate system (GCS).

3.2.3 Data Capture

The three-dimensional co-ordinates of light emitting diode (LED) markers in static and dynamic tests were obtained using three Optotrak Certus towers (Northern Digital Inc. [NDI], Ontario, Canada) at a sample rate of 100 Hz within a central calibrated volume of 1.0 m x 1.5 m x 1.5 m (root mean square error <0.45 mm). Prior to dynamic handball tests, virtual anatomical landmarks were captured using the digitisation process of the First Principles motion capture interface (NDI, Ontario, Canada). Anatomical landmarks at the hip, knee, ankle, shoulder, elbow, wrist and knuckles were virtually stored in relation to each cluster (Table 3.1).

Table 3.1

Anatomical landmarks representing rigid segments and joint centre locations

Segment	**Anatomical landmarks stored as virtual markers**
Upper-trunk (shoulders)	Lateral tip of acromion Distal-midpoint of 12th rib, lateral aspect
Lower-trunk (pelvis)	Midpoint of iliac crest Right greater trochanter (RGT), Left greater trochanter (LGT)
Thigh	Medial femoral epicondyle (MK) Lateral femoral epicondyle (LK)
Shank	Medial malleolus Lateral malleolus
Upper arm	Right lateral tip of acromion (RAP), Left lateral tip of acromion (LAP) Medial humeral epicondyle (ME) Lateral humeral epicondyle (LE)
Forearm	Ulna styloid process tip Radial styloid process tip
Hand	Dorsal aspect of second metacarpophalangeal joint Dorsal aspect of fifth metacarpophalangeal joint
Joint centre	**Location**
Trunk Origin (Mid-shoulder)	½ (RAP + LAP)
Pelvis Origin (Mid-pelvis)	½ (RGT +LGT)
Right hip [1]	¾ RGT + ¼ LGT
Left hip [1]	¾ LGT + ¼ RGT
Knee	½ (LK + MK)
Right Shoulder [2]	$(L_{upper\ arm} / 605) \cdot (0.413, -0.903, 0.121)$
Left Shoulder [2]	$(L_{upper\ arm} / 605) \cdot (-0.413, -0.903, 0.121)$
Elbow	½ (LE + ME)

[1]Greater trochanter method (Weinhandl & O'Connor, 2010). Bilateral landmark was stored within both the pelvis and the bilateral thigh segments.

[2]Fleisig's method has been used in the study of baseball and softball windmill pitching (Fleisig et al. 1996; Werner et al., 2005). As the acromion marker is stored virtually in this study, the calculation was adapted by removing the radius of the reflective marker. Bilateral shoulder joint centres were then stored within the upper-arm clusters.
$L_{upper\ arm}$ is the length of the upper arm.

This process allows the anatomical frame of each segment, the estimation of each joint centre and the joint coordinate systems to be later be calculated within Visual3D (C-Motion, Inc., Maryland, USA), and is based on the Calibrated Anatomical Systems Technique (CAST, Cappozzo, Catani, Della Croce, & Leardini, 1995). For a more detailed explanation of this process, please see Appendix F: Biomechanical model. A diagram displaying the marker clusters, anatomical frame and joint co-ordinate systems is presented in Figure 3.3.

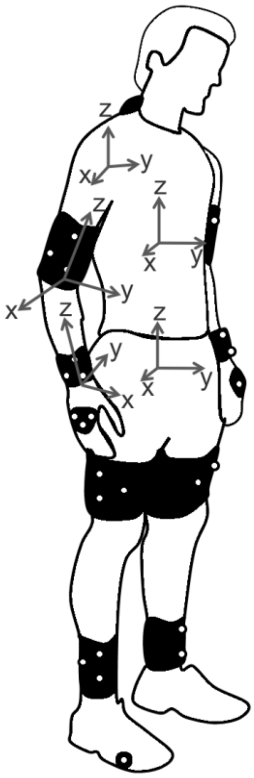


Figure 3.3: Marker cluster placement and anatomical reference frames.

3.2.4 Data processing

Three-dimensional data were imported into Visual3D for analysis. Static trial data were used for model construction for each participant and involved the calculation of joint centres and association of bone segments to the virtual anatomical markers. This model was then applied to each participant's dynamic trials. Dynamic trial raw data were interpolated using a third order polynomial where gaps up to 5 frames were present due to marker occlusion. Data were then filtered using a fourth-order low-pass Butterworth filter with a 7 Hz cut-off frequency. The cut-off frequency was determined using a residual analysis (Winter, 2009) conducted on each segment a randomly selected sample of five participants for cut-offs from 5 to 15 Hz (process described in Appendix B). The average frequency across all segments and all participants was then chosen. Velocity-time curves were visually inspected across the applied cut-offs in addition to the methods presented by Winter (2009). Equations for the estimation of optimal cut-off frequency (Yu, 1989; Yu, Gabriel, Noble, & An, 1999) indicated 9 Hz should have been used and therefore suggest that 7 Hz may have over-smoothed the data (refer to section 8.2.3 for further discussion). When *post-hoc* analyses of two key parameters (hand speed and shoulder angular velocity) were conducted however, these parameters were affected by less than 2% of reported values and the correlation between the two was altered by 0.0129, which did not change the effect size of the relationship. Thus, the use of 7 Hz was deemed appropriate and used during data processing.

Data were removed from the instant prior to ball contact onward to avoid problems related with smoothing through impact (Knudson & Bahamonde, 2001). Further, to address issues with digital filtering, ten frames were reflected at the beginning and end of the data array and were then removed post filtering. This process was conducted using Visual3D pipeline. Additional frames were removed after the filtering process. Data were analysed from the leading foot toe-off (0% movement time) until ball contact (100% movement time). The swing phase describes the punching motion from maximum back swing to ball contact, determined through assessment of position-time and velocity-time curves, which were then crosschecked through visual footage. Information on the determination of all events and phases can be found in Appendix F.

Initially a total of 64 parameters were calculated in Visual3D. The choice of these parameters was based on a deterministic model (Appendix A), coach and player feedback as to what was important, important parameters identified in two case studies (Parrington, Ball, MacMahon, & Taylor, 2009; Parrington et al., 2012), and notational analysis of handball performance in AFL games (Parrington, Ball, & MacMahon, 2013b

[Chapter 2 of this thesis]). Parameters included position data at ball contact (support hand height, lower and upper trunk height), maximum linear velocity and velocity at ball contact (striking hand, lower and upper trunk, strike side hip and shoulder), joint and segment angles at ball contact, ROM, angular velocity (maximum and at ball contact) and time to maximum (knee, hip, shoulder, elbow, lower-trunk, upper-trunk, upper-arm, forearm).

3.2.5 Statistical processing and analysis

Data per trial, per participant were exported from Visual3D and imported into Excel for management and screening. Mean and standard deviations were calculated per parameter to represent the participant for group-based assessment and to screen for univariate outliers. Group data were then imported into two statistical software programs (SPSS 20.0 and Minitab 16) for statistical analysis. Hand speed of the striking arm was used in statistical procedures as the performance parameter (dependent variable). This selection was made based on the significant positive correlation between the speed of the striking segment and the ball speed and projectile distance in maximal Australian football kicking (Ball, 2008). The alpha level for significance was 0.05 for all statistical tests, and effect sizes (medium effects, $r > 0.3$, large effects, $r > 0.5$; Cohen, 1988) are provided for additional information.

Missing data (1/19 players) from the shoulder joint and trunk due to marker occlusion at the time of ball contact were filled using multiple imputations procedures in SPSS. This procedure is suggested to be an appropriate method to treat missing data, which avoids list-wise or case-wise deletion, or mean substitution. The multiple imputations method predicts missing values, while taking into account variability of the missing data (Wayman, 2003). Diagnostic statistics to examine whether the imputed values were acceptable (e.g. assessing plot distribution and checking for imputation algorithm convergence) were assessed on each of the five imputed datasets. Proceeding statistical analyses then used the average (or pooled) results across the five imputations.

Due to the exploratory nature of this study, the 64 movement parameters (independent variables) were reduced using a supervised principal components analysis. Although principal components analysis was conducted to reduce the number of parameters and to facilitate regression analysis (Tabachnick & Fidell, 2007), the supervised principal components analysis method was used as a supplementary procedure because of the high variable to case ratio (Hastie, Tibshirani, & Friedman, 2009). The supervised principal components analysis first involved assessment of the standardised univariate regression coefficients between each movement parameter and the dependent parameter hand speed. The threshold for further inclusion was $r > 0.4$, allowing 15 parameters to be entered into the second stage of the principal component analysis. The second step involved conducting the principal components analysis in SPSS using varimax rotation. The choice of number of components (groups of parameters) was based on the following recommendations from Tabachnick and Fidell (2007): eigen-values greater than 1, scree-plot analysis, and components with three very large (> 0.7) or four large (> 0.6) loadings. Kaiser-Meyer-Olkin test of sampling adequacy (suggested cut-off > 0.5) and Bartlett's test of sphericity ($p < 0.05$) were assessed to establish the appropriateness of the factor model. One parameter was extracted to represent each of the component groups.

The parameters identified from the components analysis were then entered into a best subsets regression (Minitab) and multiple regression procedure (SPSS). The best subsets procedure calculated all possible regression combinations for the entered parameters. Choice of regression equation was determined by the trade-off between the lowest Mallow's Cp value, the highest correlation coefficient, and a 5:1 case to independent variable ratio (Tabachnick & Fidell, 2007). The chosen regression was then replicated in SPSS to extract additional information (i.e. R^2 change) that is not given during the best subsets procedure. Robustness of the regression was then assessed on a 2/3 subsample. These procedures have previously been conducted in Ball (2008).

3.3 Results

Using a supervised principal components method, the number of parameters was first reduced to 15 (Table 3.2) through the assessment of the standardised univariate regression coefficients with hand speed ($r > 0.4$ included, 49 parameters excluded). Hand speed most strongly correlated with shoulder angular velocity at ball contact, upper-arm angular velocity at ball contact, forearm maximum angular velocity, separation angle at ball contact, forearm angular velocity at ball contact and support hand position from pelvis (Table 3.3). Although negatively correlated, time to maximum upper-trunk rotation velocity, shoulder joint path at ball contact, and shoulder range of motion also returned significantly large effects. Range of forearm angle motion, shoulder angle at ball contact, and support hand vertical position from pelvis were all also significantly correlated, with medium effects. Upper-trunk orientation angle was the only parameter included in the supervised principal components analysis that had a medium effect size but was not significant.

Table 3.2

Mean and standard deviation of all parameters entered into the principle component analysis

		Mean	SD
Dependent performance variable			
Hand speed (m/s)	Resultant linear velocity of the hand segment (centre of mass) at ball contact	9.90	0.83
Angles at ball contact			
Shoulder path (°)	Angle defined by the linear velocity vector of the shoulder joint of the striking arm and the line between the shoulder and the target centre in the X-Y plane	-9	10
Upper-trunk orientation (°)	Upper-trunk segment orientation (shoulder orientation) toward target about the global vertical axis (z-axis) rotation; square to target = 0°)	-29	7
Shoulder angle (°)	Shoulder flexion-extension angle	13	10
Separation angle (°)	Relative included angle between the z-axes of the upper-trunk (shoulders) and lower-trunk (pelvis).	-4	5
Angular velocities at ball contact			
Upper-trunk rotation velocity (°/s)	Angular velocity of the upper-trunk about the global z-axis	203	64
Forearm angular velocity (°/s)	Angular velocity of the forearm about the global x-axis	966	105
Upper-arm angular velocity (°/s)	Angular velocity of the upper-arm about the global x-axis	829	132
Shoulder angular velocity (°/s)	Angular flexion velocity of the shoulder joint	809	142
Other Parameters			
Forearm maximum angular velocity (°/s)	Maximum angular velocity of the forearm about the global x-axis	980	108
Forearm angle range (°)	Difference between forearm angle maxima and minima during the swing phase about the global x-axis	62	12
Upper-arm angle range (°)	Difference between upper-arm angle maxima and minima during the swing phase about the global x-axis	49	12
Shoulder angle range of motion (°)	Difference between shoulder angle maxima and minima during the swing phase about, negative value denotes shoulder flexion	-48	14
Support hand vertical position from pelvis	Support hand vertical distance from the pelvis (% of player height) at ball contact	17%	3%
Support hand position from pelvis	Resultant support hand distance from the pelvis (% of player height) at ball contact	30%	3%
Time to max upper-trunk rotation velocity	Time to maximum upper-trunk rotation velocity as a percentage of movement time from toe-off of the front foot to ball contact	95%	4%

Table 3.3

Correlations matrix for all variables significantly correlated with hand speed

		Hand - speed	Shoulder path	Shoulder angle	Separation angle	Forearm angle range	Shoulder ROM	Forearm maximum angular velocity	Forearm angular velocity	Upper-arm angular velocity	Shoulder angular velocity	Support hand vertical position from pelvis	Support hand position from pelvis
Shoulder path	*r*	-0.54											
	p	0.016											
Shoulder angle	*r*	0.492	-0.429										
	p	0.038	0.076										
Separation angle	*r*	0.59	-0.50	0.53									
	p	0.008	0.028	0.025									
Forearm angle range	*r*	0.50	-0.36	0.43	0.13								
	p	0.031	0.126	0.077	0.590								
Shoulder ROM	*r*	-0.51	0.39	-0.56	-0.22	-0.87							
	p	0.031	0.111	0.019	0.375	<0.001							
Forearm maximum	*r*	0.61	-0.40	0.08	0.06	0.62	-0.44						
angular velocity	*p*	0.006	0.091	0.745	0.794	0.005	0.058						
Forearm angular	*r*	0.57	-0.38	0.07	0.10	0.62	-0.40	0.99					
velocity	*p*	0.011	0.105	0.797	0.677	0.005	0.092	<0.001					
Upper-arm angular	*r*	0.65	-0.56	0.39	0.26	0.76	-0.75	0.73	0.68				
velocity	*p*	0.002	0.013	0.112	0.274	<0.001	<0.001	<0.001	0.001				
Shoulder angular	*r*	0.73	-0.37	0.38	0.28	0.79	-0.80	0.74	0.70	0.92			
velocity	*p*	<0.001	0.118	0.116	0.238	<0.001	<0.001	<0.001	0.001	<0.001			
Support hand vertical	*r*	0.49	-0.28	0.50	0.33	0.02	-0.27	0.27	0.25	0.26	0.34		
position from pelvis	*p*	0.034	0.252	0.036	0.174	0.925	0.281	0.258	0.307	0.280	0.151		
Support hand position	*r*	0.52	-0.54	0.81	0.52	0.28	-0.37	0.11	0.08	0.38	0.36	0.59	
from pelvis	*p*	0.022	0.017	<0.001	0.022	0.252	0.124	0.648	0.734	0.109	0.128	0.008	
Time to max upper-	*r*	-0.66	0.47	-0.46	-0.38	-0.15	0.37	-0.42	-0.38	-0.34	-0.40	-0.70	-0.47
trunk rotation velocity	*p*	0.002	0.042	0.058	0.107	0.539	0.118	0.076	0.107	0.152	0.089	<0.001	0.044

Separation angle, shoulder angular velocity and time to maximum upper-trunk rotation velocity were chosen to represent each of the component groupings. The decision on which parameter was used was based on statistical data and theoretical information from upper-limb sports skills (Figure 3.4).

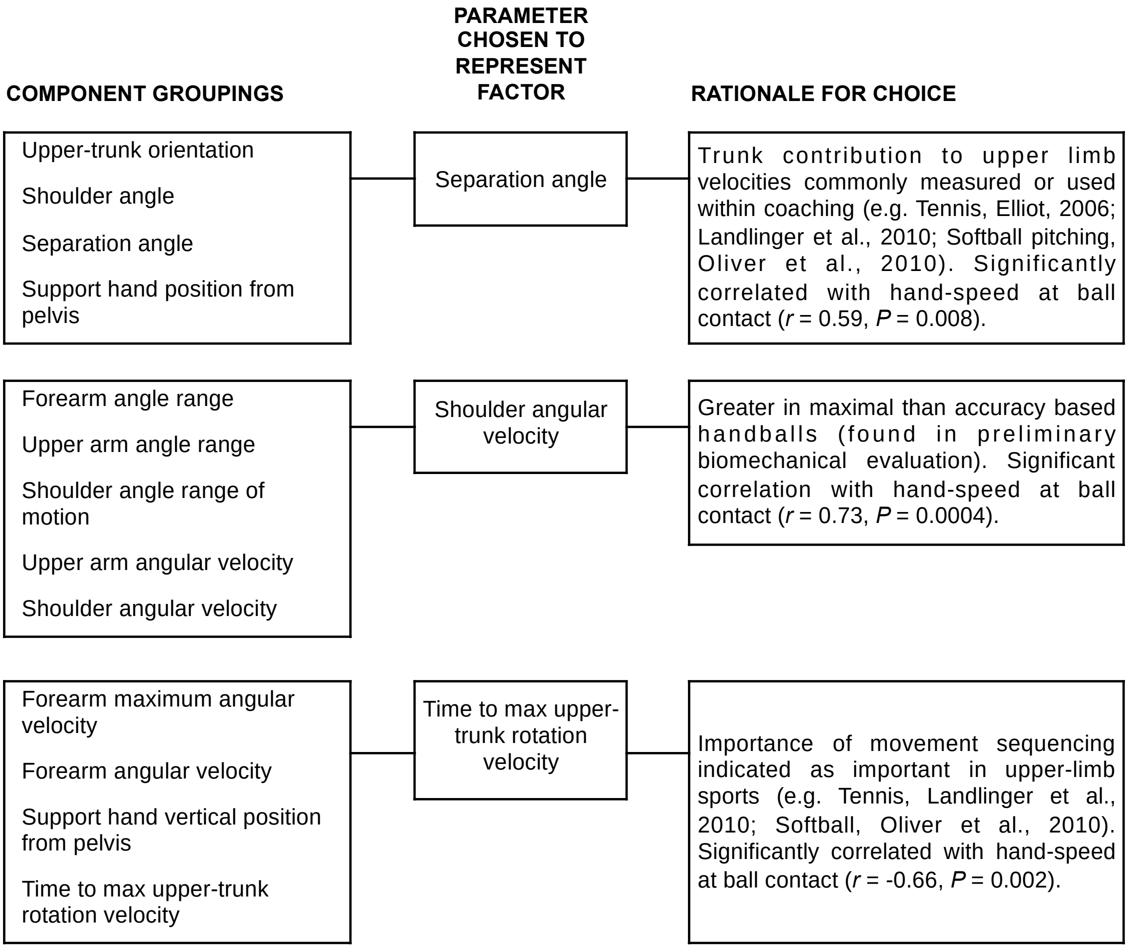


Figure 3.4: Principal components analysis with parameters chosen to represent factor group.

The optimal solution given through the best subsets procedure indicated that a regression including all three parameters had the highest R^2 and lowest total square error value (Mallow's Cp), in comparison with the two variable solutions. This regression equation explained 78% of the variance in hand speed ($p < 0.001$), and included each of the parameters chosen from the components analysis: shoulder angular velocity at ball contact, separation angle at ball contact and time to maximum upper-trunk rotation angle. Table 3.4 reports the regression analysis for the full sample and 2/3 subset analyses, including changes in R^2 (ΔR^2) for the individual parameters entered into the regression. Both shoulder angular velocity and separation angle were significantly entered into both the full and subset regressions, demonstrating robustness of these parameters.

Table 3.4

Regression analysis with hand speed as the dependent variable

			Individual parameters		
		Regression	Shoulder angular velocity	Separation angle	Time to maximum upper-trunk rotation velocity
FULL (n=19)	R^2 / ΔR^2	0.78	0.54	0.16	0.08
	p	<0.001	<0.001	0.01	0.03
SUBSET 1 (n=14)	R^2 / ΔR^2	0.72	0.32	0.31	0.09
	p	0.004	0.03	0.01	0.10
SUBSET 2 (n=14)	R^2 / ΔR^2	0.74	0.42	0.25	0.07
	p	0.003	0.01	0.01	0.14
SUBSET 3 (n=14)	R^2 / ΔR^2	0.88	0.60	0.19	0.09
	p	0.003	<0.001	0.01	0.02

3.4 Discussion

The aims of this paper were to describe the mechanics of the handball pass in Australian football, an upper-limb striking movement pattern, and to identify important technical aspects involved in maximal speed handballing. To achieve this, a supervised principal components analysis followed by multiple regression with hand speed as the dependent performance variable were implemented. Hand speed at ball contact (9.9 ± 0.83 m/s) lay between the 7.1-7.7 m/s reported for a handball accuracy task (Parrington et al., 2012) and 10.4 m/s reported for a maximal handball task (Parrington, Ball, MacMahon, & Taylor, 2009). Performance was found to relate to shoulder angular velocity, time to maximum upper-trunk rotation and separation angle.

Shoulder angular velocity was found to be the most strongly related technical factor associated with hand speed at ball contact (r = 0.73, p < 0.001). This parameter had the largest effect size for the correlation with hand speed, was significant at p < 0.001, explained the most variance in the regression analyses and was robust, indicated by the significant positive correlation for both the full and subset analyses. This finding indicated that increased shoulder angular velocity for ball contact was associated with an increased hand speed at ball contact. Of note, shoulder maximal angular velocity occurred at all contact for all participants.

Shoulder angular velocity itself was strongly correlated with upper-arm angular velocity at ball contact, forearm angular velocity (maximum and at ball contact), shoulder range of motion and forearm angle range ($r \geq 0.7$, $p \leq 0.001$). Shoulder range of motion is also an important technical parameter. A larger range over which flexion occurred at the shoulder was associated with greater shoulder angular velocity at ball contact and in addition significantly correlated with hand speed (r = 0.51, p = 0.031). With support of the fundamental link between increased range of motion and speed or force production in maximal efforts (Knudson, 2007), it could be expected that the greater range of motion would allow more shoulder angular velocity to be developed. Although upper-arm and forearm angular velocity are an outcome of shoulder joint movement, knowledge of their positive linear relationship with shoulder angular velocity may be helpful from an applied perspective for the provision of technical cues to players. For example, informing players and particularly younger athletes to swing their upper arm forward faster might be easier understood, than directing them to maximally rotate their shoulder joint in a flexion motion.

Time to maximum upper-trunk rotation velocity was the parameter next most strongly correlated with hand speed. The negative relationship (r = -0.66, p = 0.002) suggested that an earlier peak in upper-trunk rotation was associated with larger hand speed in players. These data, coinciding with the fact that maximum shoulder angular speed and maximum linear hand speed occur at ball contact, may imply a form of kinetic chain transfer from the trunk to the arm (Putnam, 1993). The earlier occurrence of maximum upper-trunk rotation prior to the timing of maximum shoulder angular velocity indicates a sequential use of joint motion. In comparison, simultaneous movement across multiple joints, associated with maximal force rather than speed development (Knudson, 2007), is represented by maximum upper-trunk rotation occurring later (at ball contact), when maximum shoulder angular velocity is occurring. This sequencing has been shown in other underarm throw-like movements such as the windmill pitch (Oliver, Dwelly & Kwon, 2010), who found similar timing of peak upper trunk rotation, late in the movement pattern but prior to ball release for both intermediate and advanced softball pitchers. It is of note that while this negative relationship existed, the range of times that maximal trunk rotation occurred was between 86-100% of movement time indicating that it occurs relatively late in the swing sequence.

Time to maximum upper-trunk rotation velocity shared a negative relationship with the distance that the support hand was held from the pelvis both in resultant direction (medium effect, $r = -0.47$, $p = 0.044$), and in the vertical position (large effect, $r = -0.7$, $p < 0.001$). This relationship indicates that a support hand lower and closer to the body was associated with a later maximum upper trunk rotation. A hand position too close to the rotation axis of the trunk may reduce the range about which the trunk can rotate prior to the hand contacting the ball and may result in a later peak rotation as players follow through the movement. As the hand is moved slightly further away, a greater range would be required to make contact, which could be related to the maximum rotation of the upper trunk occurring earlier. Meanwhile, a lower hand position that induces too much trunk flexion may have an effect the ability to rotate the upper-trunk. It is likely that there is an optimal support hand position that allows appropriate timing of peak rotation, as well as the greatest transfer of energy through the trunk, but this parameter would require further assessment.

The swing phase of the handball appears to involve a combination of lower- and upper-trunk rotations in addition to upper arm contributions. The link between rotations of the lower- and upper-trunk segments is indicated by the significant correlation between separation angle and hand speed ($r = 0.59$, $p = 0.008$). Cases where the lower-trunk was more rotated than the upper-trunk (negative separation angle) were associated with slower hand speeds. Faster hand speeds were linked with more neutral and positive separation angles, showing that the upper-trunk rotated more than the lower trunk. Although the correlation between separation angle and time to maximum upper-trunk rotation was not significant, there was a medium effect ($r = -0.38$, $p > 0.05$, Cohen, 1988). The relationship indicates that negative separation angles were associated with maximum upper-trunk rotation occurring later in the movement (approaching 100% movement time). Mechanically, it appears that when the upper-trunk was late in its peak rotation, the lower-trunk is more likely to be closed at ball contact. In contrast, when the maximum upper-trunk rotation occurs slightly earlier, it allows the upper trunk to become more closed and face the target for ball contact. Successive storage and utilisation of elastic energy by the trunk musculature provides another potential explanation for the inverted rotation relationship, which has been found in kicking (Shan & Westerhoff, 2005); however, future research would be required to test this supposition for Australian football handballing.

This study is limited by the lack of direct ball speed measurements as the three-dimensional motion capture system used did not allow for reflective (in-active) markers to be placed on the ball. As previous Australian football research has identified a correlation between striking speed (of the foot), ball speed and maximum distance, the results of this study hold the assumption that maximum hand speed and maximum ball speed are correlated.

3.5 Conclusions and coaching implications

This study has provided descriptive data for handballing for maximal speed within a large sample of elite players. In addition, it has identified three technical parameters that relate to the development of hand speed for contact with the football. This study suggests that the primary focus for coaches wishing to increase players' maximal handballing speed should be on maximising the speed of shoulder flexion during the swing phase. Increasing shoulder joint range of motion (extension-flexion) may help facilitate the production of shoulder angular velocity. Also, given faster arm speed (indicated by forearm and upper-arm angular velocity) was correlated with shoulder angular velocity, coaches could inform players to do this through cues involving "swinging the arm through faster".

Results suggest some hand speed can be accounted for by trunk motion and therefore focus should not solely be based on the arm. As support hand height and overall distance from the pelvis was related to the time of maximal trunk rotation and hand speed, players could modify their support hand position to identify the position that optimises their trunk motion and hand speed. The results also show that rotating the upper-trunk to face the target for ball contact has good potential as a coaching cue to increase hand speed.

This study determined the technical parameters that contribute to maximal effort handballing as a starting point for understanding the general movement pattern. In elite Australian football competition, statistics indicate handballing efficiency is 20% greater than kicking efficiency (Champion Data, 2012), which suggests high target accuracy at that level. Therefore, accuracy, in combination with the ability to perform maximally, may be a more potent feature of optimal performance. Future research could establish the combination of kinematic parameters that optimise performance when constrained by accuracy as well as maximal speed.

4 Study 3: Kinematics of preferred and non-preferred handballing in Australian football.

(Adapted from: Parrington, L., Ball, K., & MacMahon, C. (2014). Kinematics of preferred and non-preferred handballing in Australian football. *Journal of Sports Sciences.* Advance online publication. doi: 10.1080/02640414.2014.921830)

In Australian football, handballing proficiently with both the preferred and non-preferred arm is important at elite levels, yet little information is available for handballing on the non-preferred arm. This study compared preferred and non-preferred arm handballing technique. Optotrak Certus (100 Hz) collected three-dimensional data for 19 elite Australian football players performing handballs with the preferred and non-preferred arm. Position data, range of motion (ROM), linear and angular velocities were collected and compared between preferred and non-preferred arms using dependent t-tests. The preferred arm exhibited significantly greater forearm and upper arm ROM and angular velocity and significantly greater shoulder angular velocity at ball contact compared with the non-preferred arm. In addition, the preferred arm produced a significantly greater range of lateral trunk flexion and maximum lower-trunk speed, maximum strike-side hip-speed and hand speed at ball contact than the non-preferred arm. The non-preferred arm exhibited a significantly greater shoulder angle, lower- and upper-trunk orientation angle, but significantly lower support-elbow angle, trunk ROM and trunk rotation velocity compared with the preferred arm. Reduced ROM and angular velocities found in non-preferred arm handballs indicates a less developed skill. Findings have implication for development of handballing on the non-preferred arm.

4.1 Introduction

Handballing in Australian football involves holding the ovoid-shaped ball in one hand and striking the ball with the other hand using a clenched fist (Figure 4.1). It is the most effective method of passing to maintain possession in Australian football, with efficiency higher than kicking efficiency (80% of passes successful compared with 60%; Champion Data, 2012). The ability to use either side of the body is believed to provide an advantage over competitors who cannot and has been suggested as a requirement at the elite level (Grouios, Kollias, Koidou, & Poderi, 2002; Sachlikidis & Salter, 2007). Further, similar to the need to kick with either foot (Ball, 2011b), the competency to perform handballs on both the preferred and non-preferred hand is a necessary skill to cope with game demands in elite level competition (Parrington, Ball, & MacMahon, 2009). McLeod and Jaques (2006) suggested players should be able to pass according to the disposal direction required by the play, making mechanical equality between the preferred and non-preferred arm an important attribute for players to develop within Australian football.

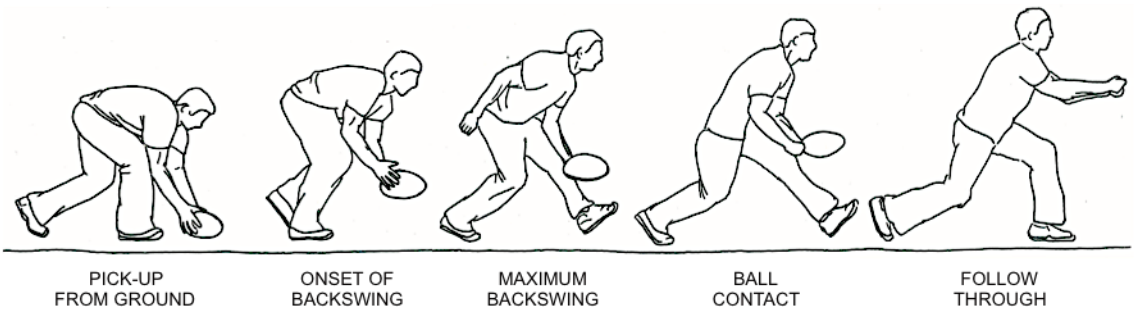


Figure 4.1: Example of handball sequence.

Reduced performance and technical differences between preferred and non-preferred arm handballing have been identified in a single subject case study (Parrington, Ball, MacMahon, & Taylor, 2009) and a technical report (*n* = 8, Parrington, Ball, & MacMahon, 2009). Parrington, Ball, MacMahon, and Taylor (2009) provided kinematic information on preferred and non-preferred arm handballs from an elite Australian football player recommended by coaches as a proficient handballer. In this study performance, characterised by both hand speed and accuracy, was better for handballs made with the preferred arm. The preferred arm handballs displayed higher linear shoulder-speed and elbow angular velocity (medium and large effects, Cohen's *d*, Cohen, 1988), while the non-preferred arm exhibited a lower shoulder angular velocity (large effect). Results of this study also suggested that the contribution of linear and angular shoulder velocity to hand speed was different between preferred and non-preferred arms. For example, the preferred hand was characterised by linear shoulder-speed values approximately double that of the non-preferred, while shoulder angular velocities were about half that of the non-preferred values (Parrington, Ball, MacMahon, & Taylor, 2009).

Parrington, Ball, and MacMahon (2009) also indicated movement pattern differences between preferred and non-preferred handballs through notational analysis in an elite sample. Stance position was different for preferred and non-preferred handballs; described as having less width, with the back foot either in line with or behind the front foot when handballing with the non-preferred arm. Preferred handballs displayed a greater degree of backswing in comparison with non-preferred handballs, providing the preferred arm a greater range of shoulder joint motion. Although Parrington, Ball, MacMahon, and Taylor (2009) and Parrington, Ball, and MacMahon (2009) identified differences between preferred and non-preferred arm handballing technique and can help guide further examination, further research is needed to establish significance and increase generalisability to the elite Australian football population.

Reduced performance and kinematic differences have been reported in the non-preferred limb for Australian football drop-punt kicking (Ball, 2011b; Smith et al., 2009). In addition, Ball (2011) found a different pattern of movement between preferred and non-preferred leg with the preferred leg kicks utilising significantly greater knee and pelvis angular velocity and ROM while non-preferred leg kicks utilised significantly larger hip ROM and angular velocity. Ball (2011) suggested differences in the degrees of freedom (Bernstein, 1967) between the preferred and non-preferred side might be underlying these different movement patterns.

Significant differences in the performance and kinematics between preferred and non-preferred upper-limb movements, such as over-arm throwing have been reported (referred to as dominant and non-dominant in these studies, Hore, Watts, Tweed, & Miller, 1996; Ning, Faro, Sue, & Hamilton, 1999; Sachlikidis & Salter, 2007; van den Tillaar & Ettema, 2006; Williams, Haywood, & Painter, 1996). Throwing performance has been reported as superior in the preferred arm for both accuracy (Hore et al., 1996) and throw velocity (Ning et al., 1999; van den Tillaar & Ettema, 2006). In addition, non-preferred throws have been described as displaying a less optimal coordination pattern (Sachlikidis & Salter, 2007), with movement patterns similar to those exhibited by novice performers (Williams et al., 1996). Van den Tillaar and Ettema (2006) reported an increased internal rotation velocity and an increased range of internal rotation movement of the shoulder in throwing with the preferred arm. Likewise, Sachlikidis and Salter (2007) reported significant differences in the lower body mechanics of non-preferred arm throws, including lower maximum lead leg knee lift and lack of lead leg knee extension during the arm acceleration phase of the throw. There were also differences in the timing of pelvic and upper torso rotation between the preferred and non-preferred arm throws, with a delay in rotation initiation occurring on the preferred side.

Less optimal coordination, novice characteristics and reduced performance identified in non-preferred skills may be related to the lack of practice completed on the non-preferred side, rather than limb dominance emanating from laterality. During the development of motor skills it is suggested that people develop the ability to coordinate available degrees of freedom required by the movement (Latesh & Levin, 2004; Yang & Scholz, 2005). Thus, novice movement characteristics may be targeted for change through skill based practice.

Research on both upper and lower limb skills have suggested that training the non-preferred limb to mirror the preferred limb may improve technique on the non-preferred side (Kicking, Ball, 2011b; throwing, Sachlikidis & Salter, 2007). Therefore, the identification of technical differences between preferred and non-preferred arm handballing has practical implications for the development of the non-preferred arm by allowing the key components of the movement to be addressed in the less efficient movement pattern. The work by Parrington and colleagues (2009) provided a starting point for this analysis, but further work is needed on a larger sample of Australian football players to increase the generalisability of the results and establish significant differences. This information may help direct coaches in their provision of training cues to assist players. The aims of this study were therefore to compare performance and examine the kinematic differences between preferred and non-preferred arm handballs in a large sample of elite players.

4.2 Methods

Nineteen male professional Australian football players (19 ± 1.5 years, 1.9 ± 0.1 m, 84.6 ± 7.8 kg, 16 right-hand preferred, 3 left-hand preferred) contracted to play for one of two elite first tier Australian Football League (AFL) teams or their associated second tier feeder Victorian Football League (VFL) club participated in this study. Players were playing or completing pre-season training at the time of testing. All research methods were approved by the university human research ethics committee and players were required to provide signed inform consent prior to testing.

Prior to testing participants completed a standardised five-minute warm up on either a treadmill or cycle ergometer (50-70% effort), followed by a minimum of five handballs on each hand to become familiar with the test and equipment. The test was completed using an Australian football (Sherrin, Australia; official AFL game ball), which had been inflated within the AFL official pressure range of 62-76 kPa. Handballs were performed into a net that dropped from the laboratory ceiling situated in front of a target placed beyond the net, 5.5 m from the centre of the capture area and aligned with the Y-axis of the global coordinate system (Figure 3.2 Chapter 3, also see Global reference system, Appendix F). The target centre was 1.5 m high and 0.2 m in diameter, which approximated a mid-chest height catching position. The target was used only as a reference point to direct handballs and thus, no accuracy measurements relative to this target were taken. Players were instructed to complete the handball trial at game intensity and perform the handpass the ball toward the centre of the bulls-eye target with maximal speed. Testing required players to complete five good handballs using each the preferred and non-preferred arm. A good handball was defined by the player as 'representative of their normal performance', and atypical trials where the participant reported that it 'did not feel right' were repeated. This method was used in order to get the best representation of the mean performance of the athlete. To simulate a dynamic situation, players were required to first catch the ball at mid-chest height and then perform the handball, as described in Chapter 3. All participants completed their preferred arm handballs first.

Each player wore training attire, training shoes and had rigid-body marker-clusters fitted for testing. Clusters were created using heat-mouldable plastic, which hardened at room temperature. Three non-collinear markers were attached on the outer surface and Velcro hook was bound to the underside of the cluster. Neoprene (1 mm) with rubber exposed on one side and Velcro loop on the other, was firmly wrapped, rubber side in contact with skin, about the bilateral hand, forearm and upper-arm. Clusters positioned on the lower-trunk (at the height of the posterior superior iliac spine), upper-trunk (at the position of C7) were attached using strong adhesive double-sided tape. Sports tape was used in addition to secure each cluster. The use of marker clusters was chosen in preference to individual skin-mounted markers as individual markers positioned on anatomical landmarks are subject to error due to skin movement artefact. In contrast, the use of marker clusters and an under wrapping, distal attachment location have been identified as methods that provide superior tracking of segments (Cappozzo, Catani, Leardini, Benedetti, & Della Croce, 1996; Manal, McClay, Stanhope, Richards, & Galinat, 2000) and have been used previously in handballing research (Parrington et al., 2012). All players reported feeling accustomed to and not restricted by the clusters that were attached. Anatomical landmarks were virtually stored in reference to each cluster using a digitising probe (NDI, Ontario, Canada), in the experimental set up procedure (First Principles, NDI, Ontario, Canada). Landmarks on the lower-trunk (left/right greater trochanter and iliac crest), upper-trunk (left/right acromion process, lateral aspect of the 12th rib), upper-arm (medial and lateral epicondyles), forearm (radial and ulna styloid process) and hand (2nd and 5th knuckle; Parrington et al., 2012), created the anatomical frame for each segment. Segment and joint definitions (Table 4.1 & Figure 4.2) have been adapted from the recommendations of Wu et al. (2002; 2005) to fit with the x, y, z axis definitions used throughout this thesis.

Table 4.1

Segment and joint definitions

Origin	**Location**	**Calculation**
Lower-trunk	The mid-point between the right and the left greater trochanter (RGT/LGT)	= ½ (RGT + LGT)
Upper-trunk	Midpoint between the right and left acromion processes (RAP/ LAP)	= ½ (RAP + LAP)
Upper arm	Shoulder joint centre: modification of offset prediction method used in other upper-extremity sport analysis. Located along the z-axis. L_h is the length of the upper arm.	Right = $(L_h / 605) \cdot (0.413, -0.903, 0.121)$ Left = $(L_h / 605) \cdot (-0.413, -0.903, 0.121)$
Forearm	Elbow joint centre: The midpoint between the medial and lateral humeral epicondyles (MHE/LHE). Located in line with the z-axis.	= ½ (MHE + LHE)
Hand	Wrist joint centre: The midpoint between the radial and ulnar styloid process (RSP/USP). Located in line with the z-axis.	= ½ (RSP + USP)

Parameter	**+**	**-**
Lower-trunk orientation	Forward rotation	Backward rotation
Upper-trunk orientation	Forward rotation	Backward rotation
Elbow angle	Flexion	Extension
Shoulder angle	Flexion	Extension
Shoulder-hip extension/flexion	Backward extension	Forward flexion
Lateral trunk flexion	Deviation to striking hand side	Deviation to support hand side
Hip-Shoulder separation	Upper-trunk rotated forward of lower-trunk	Lower-trunk rotated forward of upper-trunk
Hand path X-Y plane	Moving across the body	Moving away from the body

Note: Shoulder joint (Fleisig et al. 1996; Werner et al., 2005) calculation modified to accommodate virtual acromion marker.

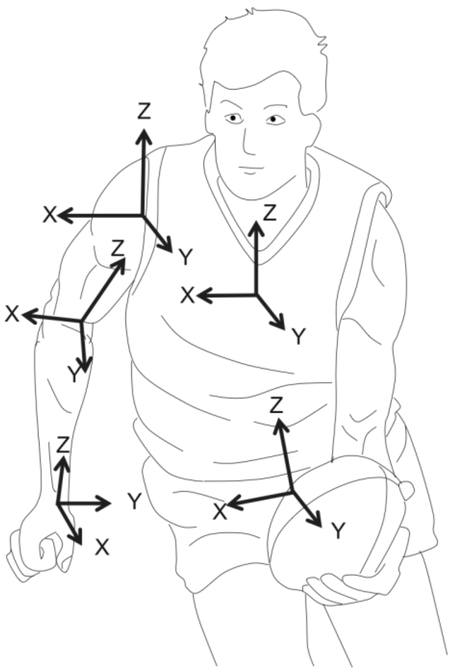


Figure 4.2: Joint and segment coordinate systems.

Three-dimensional data were collected using an Optotrak Certus motion analysis system (NDI, Ontario, Canada) sampling at 100 Hz. Three towers were arranged in a ‘Y’ configuration about a central calibrated volume, with one camera either side of the handball and one camera behind. Raw data were modelled and processed using Visual3D. Data were analysed between front foot toe-off and ball contact, which were identified visually through examination of position-time curves and crosschecked with two-dimensional video footage. Data were removed from ball contact onward, with remaining data reflected for ten frames prior to filtering with a Butterworth fourth order filter (7 Hz, Parrington et al., 2012). After the filtering process, the reflected frames were then removed. This process was conducted to avoid smoothing across impact (Knudson & Bahamonde, 2001).

Segment and joint positions, velocities, angles and angular velocities were all calculated through a Visual3D pipeline. A three-point central differences method was used in the calculation of linear and angular velocities. Joint angles were calculated locally in reference to the proximal segment and segment angles were calculated relative to the global laboratory axis. Handballing is an under-arm motion, where the upper arm does not reach 90° abduction. Therefore, Gimbal lock did not exist as a concern and only flexion-extension was assessed. The mean for each player for each parameter across five good trials for preferred and non-preferred arm was calculated in Microsoft excel and used in group-based analysis. Data were imported into SPSS 20.0 and screened for outliers prior to statistical processing. Differences between preferred and non-preferred arm handballs were assessed using a combination of paired t-tests ($\alpha = 0.05$), effect size (Cohen’s *d*; small = 0.2, medium = 0.5, large = 0.8, Cohen, 1988) and 95% confidence intervals.

4.3 Results

Parameter definitions and descriptive data (mean and standard deviation) are provided in conjunction with effect sizes for the difference between preferred and non-preferred hands in Table 4.2.

Table 4.2

Descriptive data for preferred and non-preferred arm

		Preferred		Non-preferred		Effect
		Mean	SD	Mean	SD	classification
Position data at ball contact						
Support hand height		0.69	0.09	0.69	0.09	No effect
Lower-trunk height		1.02	0.07	1.03	0.07	No effect
Upper-trunk height		1.25	0.08	1.25	0.09	No effect
Angles at ball contact (°)						
Lower-trunk orientation		-26	7	-33	10	Medium
Upper-trunk orientation		-29	7	-34	7	Medium
Forearm angle	About global x-axis	29	9	26	10	Small
Upper arm angle	About global x-axis	-40	8	-37	10	Small
Elbow angle		69	8	64	13	Small
Support arm elbow angle		39	12	46	15	Medium
Shoulder angle		15	7	23	10	Large
Shoulder-hip extension/flexion		-30	7	-31	9	No effect
Lateral trunk flexion		-4	4	-7	4	Medium
Hip-Shoulder separation		-4	5	-3	5	No effect
Vector path/ direction (°)		8	5	10	7	Small
Range of motion (°)						
Lower-trunk orientation range		17	5	12	5	Large
Upper-trunk orientation range		20	3	16	4	Large
Forearm		62	12	53	12	Medium
Upper arm		49	12	41	14	Medium
Elbow ROM		-13	5	-13	4	No effect
Shoulder ROM		-47	15	-43	15	Small
Shoulder-hip extension/flexion		-1	4	0	2	No effect
Lateral trunk flexion		3.1	2.3	1.7	2.0	Medium
Hip-Shoulder separation		5	3	5	2	Small
Linear velocity (m/s)						
Strike side hip-speed (max)		1.33	0.26	1.19	0.32	Small
Strike-side shoulder-speed (max)		1.87	0.40	1.84	0.41	No effect
Upper-trunk (max)		1.50	0.31	1.52	0.33	No effect
Lower-trunk (max)		1.15	0.21	1.05	0.25	Small
Hand speed (BC)		9.90	0.83	9.45	0.88	Medium
Strike side hip-speed (BC)		1.13	0.28	1.04	0.31	Small
Strike-side shoulder-speed (BC)		1.61	0.44	1.57	0.41	No effect
Upper-trunk (BC)		1.20	0.34	1.22	0.33	No effect
Lower-trunk (BC)		0.91	0.22	0.88	0.21	No effect
Angular velocities (°/s)						
Lower-trunk rotation velocity (max)		182	56	147	52	Medium
Elbow angular velocity (max)		207	61	228	59	Small
Lower-trunk rotation velocity (BC)		143	76	93	68	Medium
Upper-trunk rotation velocity (BC)		203	64	163	67	Medium
Forearm angular velocity (BC)		966	105	899	109	Medium
Upper arm angular velocity (BC)		834	134	747	118	Medium
Elbow angular velocity (BC)		144	62	190	64	Medium
Shoulder angular velocity (BC)		810	142	725	144	Medium
Shoulder-Hip rotation velocity (BC)		95	31	91	25	No effect

Note: Upper arm and shoulder angular velocity at ball contact = maximum; Upper-trunk orientation, hip-shoulder separation rotation velocity and forearm angular velocity maximum and at ball contact were highly correlated ($r > 0.95$)

At ball contact, the preferred arm exhibited a significantly smaller shoulder flexion angle, support-elbow flexion angle and smaller lower- and upper-trunk orientation angles, in comparison with the non-preferred arm (Table 4.3). The preferred arm handballs produced a significantly greater ROM for the upper- and lower-trunk, forearm and upper arm segments and lateral trunk flexion (Table 4.4).

Table 4.3

Joint and segment angles at ball contact (°)

		Mean diff	**95% Confidence Lower**	**95% Confidence Upper**	***p***	***d***
Trunk-orientation	Lower-trunk orientation	6	2	11	0.008	0.71
	Upper-trunk orientation	5	0	9	0.037	0.65
Elbow	Support arm flexion-extension	-8	-12	3	0.002	0.53
Shoulder	Flexion-extension	-9	-13	-4	0.001	0.86

Table 4.4

Range of motion (°)

		Mean diff	**95% Confidence Lower**	**95% Confidence Upper**	***p***	***d***
Trunk-orientation range	Lower-trunk orientation	5	2	7	0.001	0.88
	Upper-trunk orientation	4	2	5	0.0003	0.98
Forearm	X – global range	9	4	15	0.003	0.72
Upper arm	X – global range	7	2	12	0.007	0.57
Pelvis-trunk	Lateral trunk flexion range	1.4	0.3	2.4	0.014	0.51

The preferred arm handballs displayed significantly greater maximum lower-trunk speed, maximum strike-side hip-speed and hand speed at ball contact (Table 4.5). The preferred arm produced a significantly greater maximum lower-trunk rotation velocity and greater trunk rotation (lower and upper), forearm, upper arm and shoulder angular velocities at ball contact in comparison with the non-preferred arm. Elbow angular velocity at ball contact was greater in the non-preferred arm (Table 4.6).

Table 4.5

Linear velocities (m/s)

		Mean diff	**95% Confidence Lower**	**Upper**	***p***	***d***
Velocity at Ball Contact (m/s)	Hand speed	0.45	0.06	0.82	0.018	0.52
Maximum Velocity (m/s)	Strike side hip-speed	0.14	0.01	0.26	0.024	0.47
	Lower-trunk	0.09	0.02	0.16	0.013	0.40

Table 4.6

Angular velocities (°/s)

		Mean diff	**95% Confidence Lower**	**Upper**	***p***	***d***
Maximum angular velocity	Lower-trunk rotation	34	8	60	0.012	0.61
Velocity at ball contact	Lower-trunk rotation	50	11	90	0.016	0.67
	Upper-trunk rotation	40	16	64	0.003	0.60
	Forearm	66	8	125	0.027	0.60
	Upper arm	88	26	150	0.008	0.63
	Elbow	-46	-79	-13	0.010	0.50
	Shoulder	85	22	148	0.011	0.58

4.4 Discussion

Hand speed was greater in the preferred arm handballs in comparison with the non-preferred handballs. This supported the findings Parrington, Ball, MacMahon, and Taylor (2009), although both preferred arm hand speed (9.9 m/s) and non-preferred arm hand speed (9.45 m/s) found in this study were slower than those previously presented (10.4 m/s and 10.1 m/s, for preferred and non-preferred handballs, respectively). Any disparity could be explained by skill level. The athlete in Parrington, Ball, MacMahon, and Taylor (2009) was recruited from one AFL club, suggested for testing as having good technique, whereas the participants used in this study were elite Australian footballers recruited from both AFL and VFL clubs, which may have resulted in some slower hand speeds and a slower group mean value. Additionally, the player sample may explain the difference in effect size, with only medium effects found in this study compared with large effect size in Parrington, Ball, MacMahon, and Taylor (2009). In this study a number of players self-reported competency to handball using either hand before nominating their preferred hand. It is logical that players with greater ambidexterity will be more likely to produce similar hand speeds and therefore reduce the size of the difference for the within-group statistics.

For maximal handballs, outcome based on hand speed suggests superior performance from the preferred arm in comparison with the non-preferred arm. Greater performance using the preferred limb has also been shown in over-arm throwing (accuracy, Hore et al., 1996; throw-speed and accuracy, Sachlikidis & Salter, 2007). In addition, similar findings have been found in drop-punt kicking in Australian football (Ball, 2011b) with preferred-leg kicks displaying larger distal segment (foot) speed in comparison with non-preferred leg kicks.

Faster hand speeds produced by the preferred arm may be a result of greater use of the trunk (lower and upper) and arm (Upper arm and forearm) segments in comparison with the non-preferred arm. The ROM of the trunk (lower and upper), forearm and upper arm and lateral trunk flexion range were all significantly larger in the preferred arm. This larger range of motion may assist in the development of end-point speed in the preferred arm handballs, by increasing the time over which the hand can be accelerated for ball contact. The magnitudes of linear and angular velocity, excluding elbow angular velocity at ball contact, were significantly faster in the preferred arm in comparison with the non-preferred arm handballs. An example of the positive relationship between range of motion and angular velocity is given in Figures 4.3 and 4.4, for the lower-trunk and upper arm.

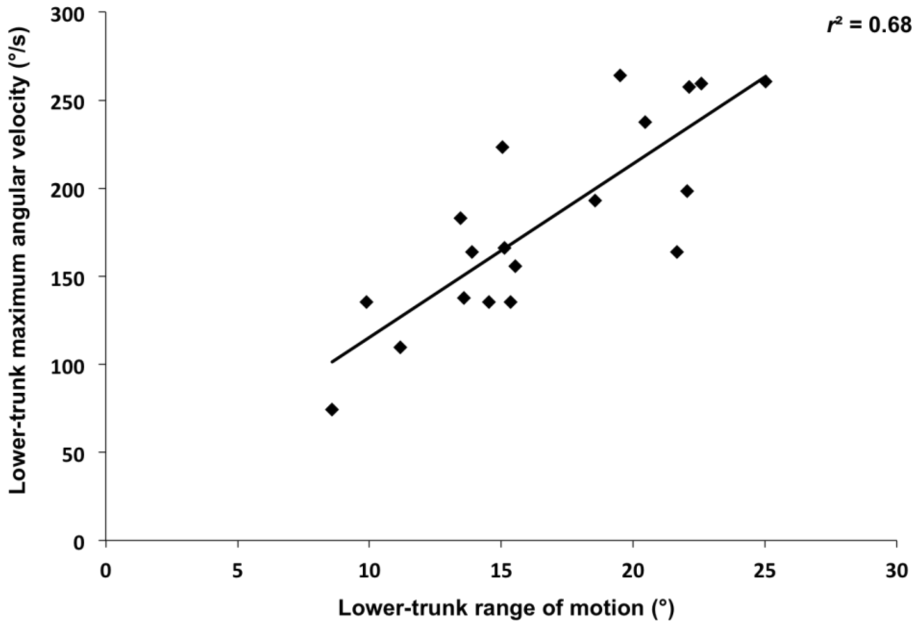


Figure 4.3: Relationship between lower-trunk range of motion and rotational velocity.

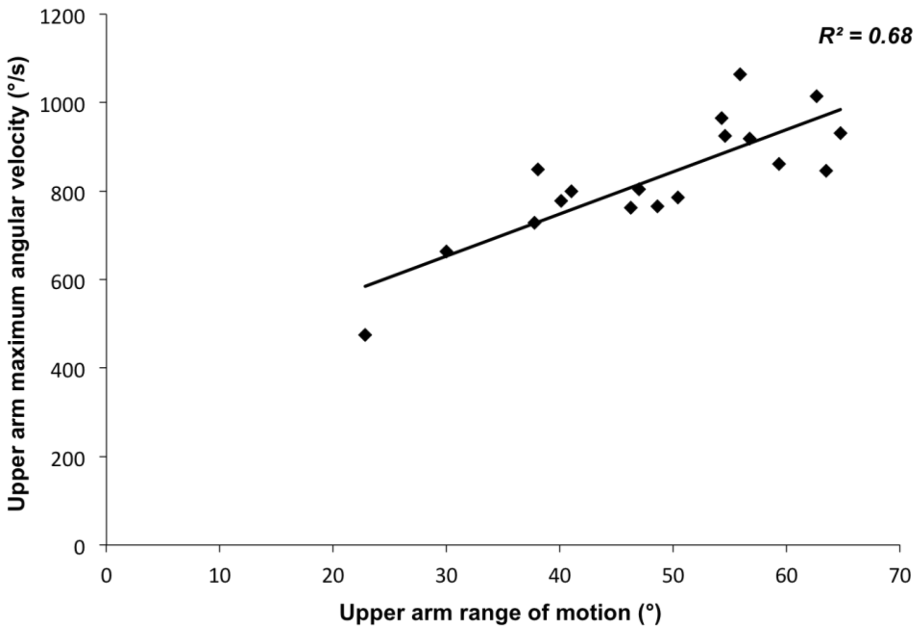


Figure 4.4: Relationship between upper arm range of motion and angular velocity.

The smaller ROM occurring in the trunk and arm in non-preferred arm handballs would result in the swing phase of the handball occurring over a shorter distance, reducing the time available to accelerate the hand. Similar findings have been indicated for overarm throwing, where the non-preferred arm exhibited a shorter time in which the arm was in the acceleration phase, resulting in reduced time in which energy could be transferred to the ball (Sachlikidis & Salter, 2007). Although handballing involves striking the football with the fist, in comparison to releasing a ball at the fingers, the development of hand speed through the swing phase for ball contact is as important as developing hand speed for ball release in overarm throwing. For Australian football kicking, Ball (2008) indicated that ball-speed was significantly linearly related to foot-speed and, therefore, hand speed imparted on the ball is likely to affect the ball-speed in a similar fashion when handballed. However, unlike throwing, handballing requires the ability to make adequate contact with the ball. Therefore, the smaller ROM and angular velocity from both proximal and distal segments may be an attempt to stabilise the hand for correct hand-to-ball contact in the non-preferred arm handballs.

The preferred arm exhibited greater rotational velocities (both maximal and at ball contact) of the trunk (lower and upper), as well as greater linear speed of the lower-trunk in comparison with handballs performed on the non-preferred arm. Linear and rotational velocity of the trunk have been linked to performance in other upper-limb ball-skills. For example, horizontal velocity during the pre-delivery stride has been shown to share a strong relationship with ball release speed in cricket bowling (Glazier, Paradisis, & Cooper, 2000). Sachlikidis and Salter (2007) found similar results in the acceleration phase of throwing, with non-preferred throws exhibiting less pelvic and upper-torso rotation. A result of the reduced peak rotations of the lower- and upper-trunk is that less energy would be available for transfer through the kinetic chain to the smaller distal arm segments (Sachlikidis & Salter, 2007). Further, in the non-preferred arm handballs, reduced angular velocities in the distal joints and segments (excluding the elbow) may stem from the initial lack of linear and rotational drive from the trunk.

The initiation of joint movements in overarm throwing has been shown to occur in a proximal-to-distal sequence (van den Tillaar & Ettema, 2009). Should handballing follow a similar proximal-to-distal initiation sequence, then the smaller magnitude of linear velocity and rotational velocities initiated at the lower-trunk in the non-preferred handballs may mean that a smaller magnitude of energy and momentum is passed through each segment to the distal hand segment. In comparison, handballs made on the preferred side may have made greater use of transfer from the proximal segments (lower- and upper-trunk) through to more distal segments (upper arm and forearm). The increased elbow angular velocity in the non-preferred arm may be an effort to counter the reduced linear and angular velocities characterising the movement and still produce a functional maximal hand speed for ball contact.

Reduced performance in the non-preferred handballs may be representative of a less developed motor pattern in the non-preferred arm. Further, kinematic differences are indicative of a different movement pattern between preferred and non-preferred handballs, rather than a scaling of the preferred arm handball. For example, results exhibit significantly larger elbow angular velocity but significantly lower shoulder angular velocity at ball contact in the non-preferred arm. Despite the elite sample used, players may have not yet developed the appropriate full body coordination and solution to joint configuration on the non-preferred limb.

A less developed skill is indicated in results, for example, by the smaller ROM across multiple segments in the non-preferred arm handballs. Reduction of joint motion is linked to the degrees of freedom problem (Bernstein, 1967), which has been hypothesised as one theory that may help to explain the differences in movement patterns between preferred and non-preferred leg kicking kinematics (Ball, 2011b). Results of this study may be better described by the principle of motor abundance. This principle suggests that the degrees of freedom in a system are abundant and that, rather than eliminating or freezing joint motions, each element is involved to allow stability and/or flexibility in the movement (Latesh & Levin, 2004). Further, Yang and Scholz (2005) indicated that learning involved developing the ability to coordinate the available degrees of freedom required to stabilise performance. As the outcome of the task is to provide maximal speed to the ball through hand speed at ball contact, it is possible that the greater elbow angular velocity in the non-preferred arm was an effort to speed up the hand segment. That is, in order to provide a functionally similar outcome on the non-preferred arm, the larger elbow angular velocity may have been an attempt to counter the smaller ROM and reduced angular velocities occurring in the more proximal segments (i.e. lower- and upper-trunk).

Another possible explanation linked to a strategy of coordinating the degrees of freedom to stabilise performance may be related to compensatory arm-trunk coordination for the control of endpoint trajectory of the hand for ball contact. Studies addressing pointing using the upper-limb found that endpoint peak velocity and endpoint trajectory error were affected by target location and the recruitment of the trunk (Archambault, Pigeon, Feldman, & Levin, 1999). It is plausible that when handballing with the non-preferred side, confidence in correctly connecting with the ball in an appropriate position was lower than using the preferred hand. Archambault et al. (1999) indicated that endpoint planning influenced movement. In addition, different movement patterns were used when the trunk was involved and that shoulder and elbow motion compensated for that trunk motion. Endpoint trajectory planning may occur when using the non-preferred arm to handball, if players were conscious of the contact position of their fist with the ball. This suggests a method of modifying the degrees of freedom through decreased proximal joint and segment movements and increased distal joint movement in the non-preferred limb to control hand speed at ball contact as well as the point of contact with the ball to provide a functionally similar outcome to the preferred arm handballs.

Given a lack of practice is believed to influence the control of the rotation of proximal joints, with less precise control resulting from reduced practice hours (Hore et al., 1996), it would be beneficial to increase the number of handballs performed on the non-preferred side during practice. Training the non-preferred arm to mirror the preferred arm may improve technical proficiency and two-handedness within Australian football game play. To increase handballing ambidexterity, players should increase forward linear motion, rotation speed of the trunk and swing the upper-arm. Increasing the range of motion in the trunk and arm may assist rotational speed development.

As hand speed was used as an indicator of performance in this study, it should be noted that this study was limited by the inability to collect direct three-dimensional information on the ball because of the active marker tracking system used. Collecting three-dimensional ball information and accuracy data should be targeted in future handballing studies. There are also a number of other future directions that exist for work examining handballing in Australian football. The assessment of coordination differences between preferred and non-preferred arm may provide additional information, as suggested for drop-punt kicking (Ball, 2011b). Given different movement patterns were evident in this study, it is appropriate to further explore these differences and how they are coordinated. Handballs are performed under complex cognitive situations and efficiency has been shown to decrease under pressure and when less passing options are available (Parrington, Ball, & MacMahon, 2008; Parrington et al., 2013b [Chapter 2 of this thesis]). Therefore, assessing handball kinematics concurrently under decision-making conditions is an appropriate future direction. Finally, an understanding of the kinetics involved in handballing may provide valuable information to coaches and players wishing to implement training to improve technique.

4.5 Conclusions

This study has provided technical information for preferred and non-preferred arm handballing in elite Australian footballers. Kinematic differences were found between preferred and non-preferred handballing. The preferred arm exhibited greater hand speed at ball contact and greater maximum lower-trunk speed and strike-side hip-speed. Greater angular velocity values for the lower- and upper-trunk, forearm and upper arm segments (maximum and at ball contact) and greater angular velocity of the shoulder at ball contact were found for the preferred-arm. Shoulder angle, lower- and upper-trunk orientation angle and elbow angular velocity were all significantly smaller in the preferred-arm at ball contact, while support elbow angle, ROM in trunk (lower and upper), forearm, upper arm and range of lateral trunk flexion were smaller in the non-preferred arm. A more developed movement pattern was evident between the arms, with the preferred-arm making greater use of the trunk, shoulder and arm.

5 Study 4: Kinematics of a striking task: Accuracy and speed-accuracy considerations.

(Adapted from: Parrington, L., Ball, K., & MacMahon, C. (2014). Kinematics of a striking task: Accuracy and speed-accuracy considerations. *Journal of Sports Sciences.* Advance online publication. doi: 10.1080/02640414.2014.942685)

Handballing in Australian football is the most efficient passing method, yet little research exists examining technical factors associated with accuracy. This study had three aims: (a) To explore the kinematic differences between accurate and inaccurate handballers, (b) to compare within-individual successful (hit target) and unsuccessful (missed target) handballs, and (c) to assess handballing when both accuracy and speed of ball travel were combined using a novel approach utilising canonical correlation analysis. Three-dimensional data were collected on 18 elite Australian football players who performed handballs toward a target. More accurate handballers exhibited a significantly straighter hand path, slower elbow angular velocity and smaller elbow range of motion (ROM) in contrast to the inaccurate group. Successful handballs displayed significantly larger trunk ROM, maximum trunk rotation velocity and step-angle and smaller elbow ROM in comparison with the unsuccessful handballs. The canonical model explained 73% of variance shared between the variable sets with a significant relationship between hand path, elbow ROM and maximum elbow angular velocity (predictors) and hand speed and accuracy (dependant variables) found. Interestingly not all parameters were the same across each of the analyses, with technical differences between inaccurate and accurate handballers different from those between successful and unsuccessful handballs in the within-individual analysis.

5.1 Introduction

Handballing and kicking in Australian football are the two methods of legally passing the ball between players. Kicking involves striking the ball with the foot after releasing the ball from the hands. Handballing is also a striking manoeuvre, which involves supporting the ball with one hand and punching the ball with the closed fist of the other hand (Parrington et al., 2013b [Chapter 2 of this thesis]). Handball use per team per game increased 42% between 1999 and 2012 and now makes up a high contribution of disposals, with between 42% and 47% of all passes across the last five Australian Football League (AFL) seasons performed via this method (Australian Football League, 2013b). Handballing is a highly efficient passing technique, with an 84% success rate in maintaining possession, and handballs are very rarely made directly to the opposition (‘clanger’, 4%, Parrington et al., 2013b [Chapter 2 of this thesis]). Statistics such as handballing efficiency and clangers are established through the maintenance or loss of possession, placing emphasis on accuracy as a contributor to performance outcome.

Accuracy in handballing has been assessed using comparisons of successful (hits) and unsuccessful (misses) in a small sample (*n* = 4, Parrington et al., 2012). Two specific coaching cues, “square to the target” and “striking through the ball” in the direction of the target were evaluated. Parrington et al. (2012) found accurate passes were characterised by a hand path that contacted through the ball in a line directed towards the target, as opposed to striking at an angle. In relation to the assessment of the coaching cue to be “square to the target”, the results indicated the orientation of the pelvis was more closed at ball contact for accurate passes in comparison with inaccurate passes. In addition, slower hand speed, slower humeral angular velocity and a smaller upper arm range and elbow range of motion (ROM) were found. The results of

Parrington et al. (2012) were based on effect sizes only, and the study proposed that further work was required to address the technical aspects of handballing accuracy in a larger sample to establish statistically significant results and making the information more generalisable to the Australian football population.

In most sports the success of a performance outcome is based on both the speed and accuracy of ball travel (e.g. tennis serve, Blackwell & Knudson, 2002; cricket fast bowling, Phillips, Portus, Davids & Renshaw, 2012; over-arm throwing, van den Tillaar & Ettema, 2003a; 2003b). Similarly, in Australian football handballing, players strive to perform handballs with both speed and accuracy variables as considerations. Slower hand speeds reported when accuracy was the focus of the handball (Parrington, Ball, MacMahon, & Taylor, 2009) and in handballs that were successful in hitting the target (Parrington et al., 2012) were considered an indication that players may have sacrificed the speed of a pass to achieve greater accuracy; a phenomenon described as the speed-accuracy trade-off suggested for dominant arm throwing (Sachlikidis & Salter, 2007; van den Tillaar & Ettema, 2003a; 2003b).

The speed-accuracy trade off has been used to describe the inverse relationship between the speed at which a skill can be performed and the accuracy that can be achieved (Fitts, 1954). Biomechanically, this trade-off may present itself in changes to joint ROM, as increased ROM is fundamentally linked to speed or force production in maximal efforts, whilst a reduction in ROM is more effective for submaximal high accuracy movements (Knudson, 2007). Reduction in the ROM for accuracy tasks may be representative of strategic coordination of the degrees of freedom required by the task constraints (Ko, Challis, & Newell, 2003; Yang & Scholz, 2005).

Van den Tillaar and Ettema (2003b) found that ball velocity decreased when accuracy was emphasised, but reported invariant relative timing of body segment movements. Although reporting significant decreases in ball velocity for accuracy-based task instruction, ball velocity was still around 85% of maximum (van den Tillaar & Ettema, 2003a). The authors suggested that one movement technique was used regardless of instruction and that increased consistency was found when athletes were performing at near maximum force production (van den Tillaar & Ettema, 2003b). The ability to perform more consistently at near maximum force production may be explained by the impulse-variability theory (e.g. overarm throwing, Urbin, Stodden, Boros, & Shannon, 2012). The impulse-variability theory described an inverted-U function, where movement variability is said to peak at around 60% of maximum force production (Urbin, Stodden, Fischman, & Weimar, 2011), or 60% throwing velocity (Urbin et al., 2012). In comparison with the speed-accuracy trade-off, this theory suggests an increase in kinematic stability achieved with increased velocity production, which ultimately could translate to greater spatial accuracy.

In Australian football kicking research, kinematic differences between accurate and inaccurate groups of drop-punt kickers have been evaluated (Dichiera et al., 2006). Groups were divided for statistical analysis based upon their achieved accuracy in the kicking test. Greater anterior pelvic tilt at heel contact, hip flexion in both legs and greater knee flexion in the support-leg knee throughout the kicking movement were evident in more accurate kickers. The increased joint flexion was suggested as a method of increasing stability in the movement. Dividing the participants into accurate and inaccurate groups allowed the identification of what differentiates accurate from inaccurate kickers. Dichiera et al., (2006) recommended also that accurate trials for an individual could be compared against their inaccurate trials. This strategy provides information on accuracy from two perspectives. The first identifies what accurate players do that inaccurate players do not and the second tackles what errors are made when individuals miss their target.

As aforementioned, for ball sports, achieving the dual goals of both speed and accuracy of ball delivery is important for performance. For handballing, ball speed is required to increase the pass distance (projection angle dependent) or delivery speed (in order to minimise the chance of interception), while accuracy is required to appropriately place the ball for the receiving player. Canonical correlation analysis (CCA) can be used to assess the relationships shared between technical parameters and both of these performance variables (speed and accuracy).

This study aimed to identify key biomechanical factors for handballing accuracy on the preferred hand. The specific aims were to (a) compare kinematic differences between accurate and inaccurate handballers, (b) compare kinematic differences between successful and unsuccessful handballs, and (c) assess the key contributors to overall handball performance, as defined by both hand speed and accuracy.

5.2 Methods

Elite and sub-elite male Australian footballers (n = 18, 19 ± 1 years, 1.9 ± 0.1 m, 87.5 ± 8.4 kg) involved in full training at the time of testing participated in this study. The university human research ethics committee approved all methods and informed consent was obtained from participants prior to testing. Participants wore training apparel (team shorts, singlet and running shoes) and warmed up on either a treadmill or cycle ergometer for five minutes then performed at least five handballs in the test area for familiarisation. They then were instructed to perform five test handballs at a target 5 m away using an official AFL game football (Sherrin, Russell Corporation, Victoria, Australia) with an inflated pressure of 69 kPa. Players were instructed to focus on aiming for the centre of the bulls-eye target and to attempt this at game intensity after catching the ball at chest height. Ball delivery methods prior to the handball have been previously described (Chapter 3 & 4). Accuracy scores were manually recorded based on a 3-2-1-0 rating (Figure 5.1) and confirmed after testing using video footage. Where the ball struck the line directly and a target section was unable to be discerned, the trial was awarded the half rating between the sections.

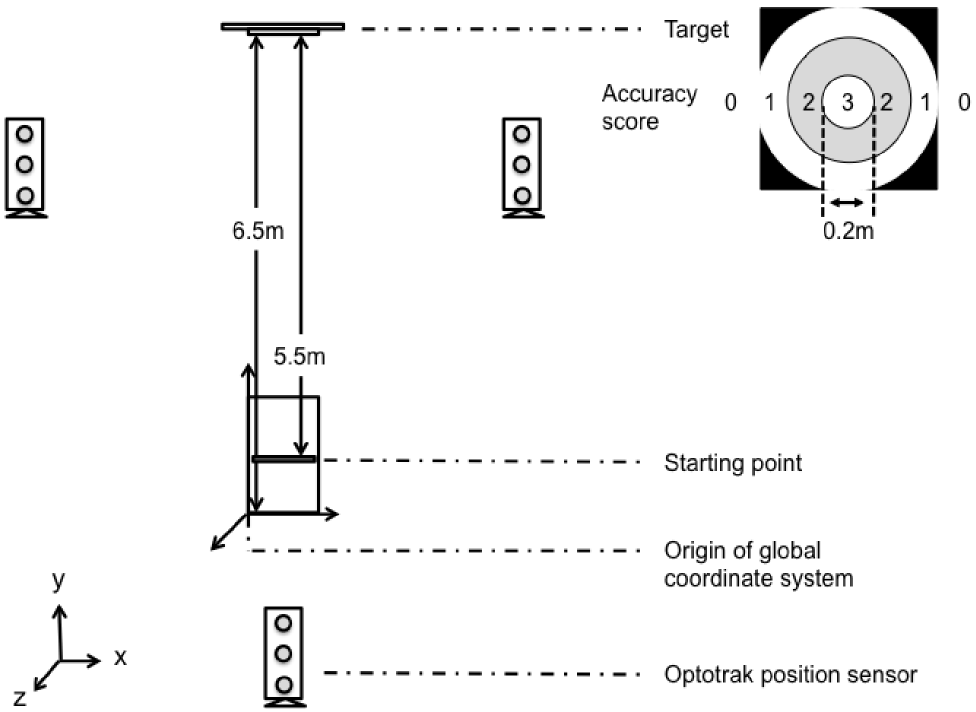


Figure 5.1: Laboratory and bulls-eye target diagram.

Reliability of accuracy scores were established through the assessment of repeated trials using percentage agreement and intraclass correlation coefficient (*ICC*). The level of agreement between the accumulated scores for five handballs was very good (percentage agreement = 97%; *ICC(2,1)* = 0.95) across two tests.

Prior to testing, rigid clusters composed of three non-collinear active markers (infrared light emitting diodes) were attached to the bilateral limbs (hand, forearm, upper-arm, shank and thigh) and the trunk (pelvis at the level of the posterior superior iliac spine, and neck situated at C7). Anatomical landmarks (2nd and 5th knuckle, radial and ulna styloid, epicondyles of the upper arm, acromion process, iliac crest, greater trochanter, epicondyles of the femur, malleoli of the ankle) were stored virtually in reference to the rigid clusters and used during data analysis in the estimation of joint centres and in the definition of anatomical reference frames of associated segments (Cappozzo et al., 1995). A single marker was placed on the base of the fifth metatarsal of both feet to assess step characteristics. Clusters were attached using a distal under-wrapping technique (Manal et al., 2000). A specialised neoprene wrap was used with rubber exposed on one side, which allowed a tight hold to the skin while other side (Velcro loop) provided a means for secure attachment of the clusters.

Three-dimensional data were collected using Optotrak Certus (100 Hz, NDI, Ontario, Canada) and First Principles software (NDI, Ontario, Canada). Data were then imported into Visual3D for modelling and processing. Raw data were analysed from leading foot toe-off until ball contact (Chapter 3, also see Appendix F). Any gaps (of up to five frames) present during this time due to marker occlusion were interpolated using a third order polynomial. To avoid smoothing across impact, data from ball contact onward were removed prior to filtering (Knudson & Bahamonde, 2001). Data were then filtered using Visual3D pipeline (4^{th} order Butterworth, 7 Hz cut-off determined through residual analysis described in Appendix B; Winter, 2009). To address distortion at the beginning and endpoints of data arrays that may occur with digital filtering, ten frames were reflected at either end of the data array during the filtering process and were then removed post filtering. Segment positions, velocities, angles and angular velocities were all calculated through Visual3D pipeline then exported to Microsoft Excel for calculation of mean and standard deviations per parameter per participant, and screening of univariate outliers. A description of all parameters is provided in Table 5.1.

Table 5.1

Parameter definitions

Parameter	Definition
Distances/ displacements	**Absolute distance (m) measured at BC:**
Support hand height	Vertical displacement of the support hand
Lower-trunk height	Vertical displacement of the lower-trunk (pelvis) origin
Upper trunk height	Vertical displacement of the upper-trunk (shoulders) origin
Support hand mediolateral position	Mediolateral distance between the support hand and the lower-trunk origin
Support hand anterioposterior position	Anterioposterior distance between the support hand and the lower-trunk origin
Support hand vertical position	Vertical distance between the support hand and the lower-trunk origin
Support hand position	Resultant distance between the support hand and the lower-trunk origin
	Relative distance (%) measured at BC as a percentage of player height:
Support hand height (%)	Vertical displacement of the support hand
Lower-trunk height (%)	Vertical displacement of the lower-trunk (pelvis) origin
Upper trunk height (%)	Vertical displacement of the upper-trunk (shoulders) origin
	Maximum distances (not at ball contact)
Step-length	Maximum distance measured between the feet. Absolute (m) and relative (%)
Striking hand maximum lateral deviation	Maximum lateral distance (m) from the lower-trunk that the striking hand achieves during the swing phase
Linear velocities (m/s)	**Resultant linear velocity measured at ball contact**
Hand speed	Hand segment (centre of mass)
Striking arm shoulder speed	Striking side shoulder joint centre
Lower-trunk speed	Lower-trunk origin
	Maximum resultant linear velocity
Maximum striking side hip speed	Hip joint centre of the striking side hip
Maximum striking side shoulder speed	Shoulder joint centre of the striking side shoulder
Maximum lower-trunk speed	Measured from the lower-trunk origin
Maximum upper trunk speed	Measured from the upper-trunk origin
Angles (°)	**Direction (vector path, °)**
Hand path	Angle defined by the linear velocity vector of the striking hand and the line between the hand and the target centre in the X-Y plane
Step-angle	Angle defined by the vector from the back to the front foot, and the line between the front foot and the target centre in the X-Y plane
Striking arm shoulder path	Angle defined by the linear velocity vector of the shoulder joint of the striking arm at ball contact and the line between the shoulder and the target centre in the X-Y plane
Lower-trunk path	Angle defined by the linear velocity vector of the lower-trunk origin at ball contact and the line between the lower-trunk and the target centre in the X-Y plane
	Segment angles at BC:
Lower-trunk orientation	Lower-trunk (pelvis) segment orientation toward target about the global vertical axis (z-axis) rotation; square to target = 0°)
Upper-trunk orientation	Upper-trunk (shoulder) segment orientation toward target about the global vertical axis (z-axis) rotation; square to target = 0°)
Forearm angle	Forearm segment angle about the global x-axis
Upper arm angle	Upper arm segment angle about the global x-axis
	Joint angles at BC:
Elbow angle	Elbow flexion angle
Shoulder angle	Shoulder flexion-extension angle
Lateral trunk flexion	Relative included angle between the x-axes of the upper-trunk and lower-trunk
Knee angle	Knee flexion-extension angle
Support elbow angle	Support elbow flexion-extension angle represented as the relative included angle
Range of motion (°)	**Difference between angle maxima and minima during the swing phase:**
Lower-trunk ROM	Lower-trunk angle about the global z-axis
Upper-trunk ROM	Upper-trunk angle about the global z-axis
Elbow ROM	Elbow joint, negative value denotes elbow flexion
Angular velocities (°/s)	**Angular velocities at BC:**
Lower-trunk rotation velocity	Lower-trunk about the global z-axis
Upper-trunk rotation velocity	Upper-trunk about the global z-axis
Forearm angular velocity	Forearm about the global x-axis
Upper arm angular velocity	Upper arm about the global x-axis
Shoulder angular velocity	Shoulder joint (represents flexion)
Elbow angular velocity	Elbow joint (represents flexion)
	Maximum angular velocity during the swing phase:
Maximum lower-trunk rotation velocity	Lower-trunk about the global z-axis
Maximum upper-trunk rotation velocity	Upper-trunk about the global z-axis
Maximum forearm angular velocity	Forearm about the global x-axis
Maximum upper arm angular velocity	Upper arm about the global x-axis
Maximum elbow angular velocity	Elbow joint (flexion)

Data were divided into three sets for subsequent analyses. To observe differences between accurate and inaccurate handballers, the first dataset (n = 18) was divided into accurate and inaccurate groups. Players were first ranked based on their accumulated accuracy score and then the sample was split into the top nine and bottom nine participants. There was a large significant difference between the two groups (d = 1.65, $p < 0.001$). Using the mean values, these groups were then compared using independent t-tests. To assess differences between successful and unsuccessful handballs, the second dataset (n = 16, two participants were removed because of all successful or all unsuccessful handballs) was composed of the mean parameter per participant for successful and unsuccessful handballs and was compared using paired t-tests. Handballs were categorised as successful (hit) if they made contact with the centre circle. A single trial was used to represent the successful handball technique in two participants who had only struck the centre of the target once. This dataset was analysed both as a whole and within accurate/ inaccurate groupings. Significance was set at an alpha level of 0.05 and effect size (Cohen's d, Cohen, 1988) and 95% confidence intervals were calculated for these analyses.

The final dataset (n = 18) was composed of the mean values for each participant and used to explore the multivariate correlations between independent and dependent variable sets. Canonical correlation analysis was conducted using three technical parameters (independent covariates) and the performance parameters target accuracy and hand speed (termed the criterion group). Three parameters were used in this study in order to fit within a reasonable case-to-IV ratio. This ratio was guided by multiple regression guidelines, which indicate a minimum case-to-IV ratio of 5:1, as there are no strict guidelines for CCA (Tabachnick & Fidell, 2007). Lower ratios are indicated as acceptable when the reliability of the data is high. In order to reduce the number of parameters entered into the analysis, Pearson's correlations were assessed initially for relationships exhibiting $r > 0.4$ with accuracy used in further analysis.

Interpretation of CCA involves three steps, (a) assessment of the full canonical model, (b) assessment of canonical functions, and (c) interpretation of structure coefficients (Figure 5.2).

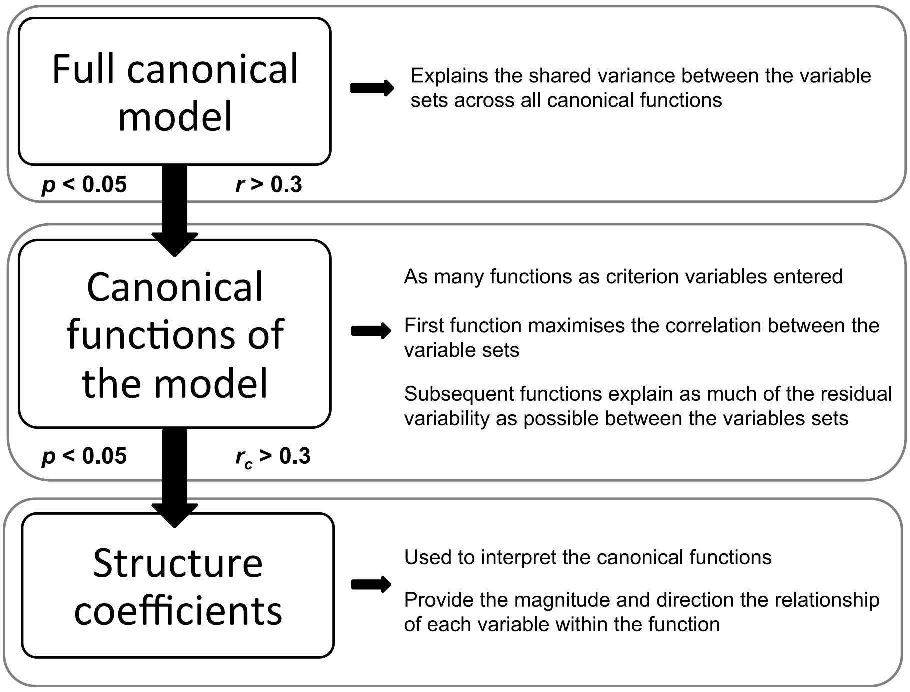


Figure 5.2: Flow chart for the interpretation of canonical correlation analysis.

The full model was assessed for the shared variance between the variable sets using a cut-off of $p < 0.05$, and the variance explained by the model was calculated using Wilks Lambda ($r^2 = 1 - \lambda$) in order to assess the effect size of the relationship against a cut-off of $r > 0.3$ (Sherry & Henson, 2005). Each canonical function was then assessed for significance ($p < 0.05$) and effect size ($r_c > 0.3$). With CCA, both r_c^2 and r_c can interpreted in the same manner as multiple regression (Hair, Tatham, Anderson, & Black, 1998; Sherry & Henson, 2005; Tabachnick & Fidell, 2007). Finally, the structure coefficients were assessed to gain an understanding of the magnitude and direction of the relationship of each variable within the function. The suggested cut-offs for meaningful correlations have been guided by the classifications within factor analysis (excellent > 0.71; very good > 0.63; good > 0.55; fair > 0.45; poor > 0.32, Tabachnick & Fidell, 2007).

5.3 Results

The accurate group produced a significantly less elbow angular velocity (both maximal and at ball contact), smaller elbow ROM and a straighter hand path at ball contact compared with the inaccurate group (Table 5.2). In the successful-unsuccessful analysis, successful handballs exhibited significantly smaller elbow ROM, larger lower-trunk and upper-trunk ROM, faster lower-trunk maximum rotation velocity and a greater step-angle in comparison with the unsuccessful handballs (Table 5.3). When the successful-unsuccessful analysis was further divided within-group, no differences were found for the accurate group, however, lower- and upper-trunk ROM and lower-trunk rotation velocity were all significantly larger in the successful handballs for the inaccurate group (Table 5.4).

Table 5.2

Descriptive data and differences for accurate and inaccurate groups

	Accurate	Inaccurate	Mean	95% Confidence		
	Mean ± *s*	Mean ± *s*	diff	Lower	Upper	*d*
Accuracy	11.9 ± 1.4	7.8 ± 1.4	4.2	2.8	5.6	1.65**
Absolute distances (m)						
Support hand height	0.68 ± 0.10	0.64 ± 0.07	0.04	-0.05	0.12	0.46
Lower-trunk height	1.04 ± 0.06	1.01 ± 0.09	0.03	-0.05	0.11	0.39
Upper trunk height	1.26 ± 0.08	1.20 ± 0.08	0.06	-0.03	0.14	0.70
Support hand mediolateral position	-0.12 ± 0.04	-0.14 ± 0.04	0.02	-0.02	0.06	0.55
Support hand anterioposterior position	-0.46 ± 0.07	-0.42 ± 0.07	-0.04	-0.11	0.03	0.55
Support hand vertical position	0.36 ± 0.05	0.37 ± 0.06	-0.01	-0.07	0.04	0.24
Support hand position	0.60 ± 0.07	0.58 ± 0.07	0.02	-0.05	0.09	0.22
Striking hand maximum lateral deviation	0.31 ± 0.02	0.30 ± 0.03	0.01	-0.02	0.03	0.25
Step-length	0.92 ± 0.20	0.96 ± 0.13	-0.04	-0.24	0.17	0.21
Relative distances (% height)						
Support hand height	36% ± 4%	36% ± 1%	1%	-3%	4%	0.22
Lower-trunk height	55% ± 2%	54% ± 3%	1%	-2%	4%	0.39
Upper trunk height	67% ± 3%	66% ± 2%	2%	-1%	5%	0.61
Step-length	50% ± 10%	52% ± 6%	-3%	-13%	7%	0.31
Resultant linear velocity at ball contact (m/s)						
Hand speed	8.23 ± 0.96	8.9 ± 1.05	-0.71	-1.72	0.29	0.68
Lower-trunk speed	1.07 ± 0.30	1.2 ± 0.41	0.05	-0.24	0.34	0.42
Maximum resultant linear velocity (m/s)						
Maximum striking side hip speed	1.12 ± 0.27	1.24 ± 0.26	-0.12	-0.39	0.15	0.44
Maximum striking side shoulder speed	1.75 ± 0.47	1.89 ± 0.42	-0.14	-0.59	0.31	0.31
Maximum lower-trunk speed	1.06 ± 0.26	1.17 ± 0.27	-0.11	-0.37	0.16	0.40
Maximum upper trunk speed	1.40 ± 0.38	1.55 ± 0.32	-0.16	-0.51	0.19	0.45
Direction (vector path, °)						
Hand path	0 ± 2	3 ± 3	-3	-5	0	1.04*
Lower-trunk path	8 ± 8	14 ± 11	-6	-16	4	0.57
Segment angles at ball contact (°)						
Lower-trunk orientation	-26 ± 7	-28 ± 4	1	-5	8	0.21
Forearm angle	28 ± 8	25 ± 9	2	-6	11	0.29
Upper arm angle	-38 ± 4	-43 ± 8	5	-1	12	0.77
Joint angle at ball contact (°)						
Elbow angle	63 ± 9	69 ± 10	-6	-15	4	0.61
Lateral trunk flexion	-6 ± 4	-5 ± 4	-1	-5	3	0.32
Knee angle	-34 ± 9	-38 ± 11	4	-6	15	0.43
Support elbow angle	39 ± 15	42 ± 15	4	-18	11	0.25
Range of motion (°)						
Lower-trunk ROM	10 ± 4	12 ± 6	-2	-8	3	0.42
Upper-trunk ROM	14 ± 3	16 ± 4	-3	-7	1	0.66
Elbow ROM	-6 ± 7	-13 ± 8	7	0	14	0.87*
Maximum angular velocity (°/s)						
Maximum lower-trunk rotation velocity	111 ± 41	139 ± 53	-28	-75	19	0.58
Maximum upper-trunk rotation velocity	122 ± 16	162 ± 60	-40	-87	7	0.82
Maximum forearm angular velocity	794 ± 152	887 ± 133	-93	-236	49	0.64
Maximum upper arm angular velocity	669 ± 119	702 ± 129	-33	-157	91	0.27
Maximum elbow angular velocity	151 ± 55	220 ± 36	-68	-115	-22	1.20**
Angular velocities at ball contact (°/s)						
Lower-trunk rotation velocity	64 ± 48	95 ± 82	-31	-98	36	0.46
Upper-trunk rotation velocity	108 ± 16	153 ± 69	-45	-99	9	0.82
Forearm angular velocity	787 ± 150	878 ± 129	-91	-230	48	0.63
Upper arm angular velocity	668 ± 118	701 ± 130	-33	-157	91	0.27
Shoulder angular velocity	634 ± 106	702 ± 140	-68	-192	56	0.54
Elbow angular velocity	139 ± 54	204 ± 28	-65	-108	-22	1.21**

*Significant difference $p < 0.05$; **Significant difference $p < 0.01$

Table 5.3

Descriptive data and differences for successful and unsuccessful handballs

	Successful Mean ± *s*	Unsuccessful Mean ± *s*	Mean diff	95% Confidence Lower	Upper	*d*
Absolute distance (m)						
Support hand mediolateral position	-0.12 ± 0.04	-0.13 ± 0.04	0.01	0.00	0.02	0.21
Maximum linear velocity (m/s)						
Maximum striking side hip speed	1.20 ± 0.28	1.14 ± 0.26	0.06	-0.01	0.12	0.22
Direction (vector path, °)						
Step-angle	3 ± 6	1 ± 7	2	0	3	0.32*
Striking arm shoulder path	-6 ± 6	-8 ± 6	1	0	3	0.25
Segment angles at ball contact (°)						
Upper-trunk orientation	-25 ± 4	-25 ± 4	-0.1	-1	1	0.33
Joint angle at ball contact (°)						
Shoulder angle	21 ± 6	22 ± 6	-1	-3	1	0.31
Support elbow angle	38 ± 14	37 ± 13	-1	-1	4	0.23
Range of motion (°)						
Lower-trunk ROM	12 ± 6	10 ± 5	2	1	3	0.31**
Upper-trunk ROM	15 ± 4	14 ± 3	1	0	2	0.36**
Elbow ROM	-9 ± 8	-11 ± 8	2	0	3	0.21*
Maximum angular velocity (°/s)						
Maximum lower-trunk rotation velocity	128 ± 51	117 ± 45	11	1	22	0.24*

*Significant difference $p < 0.05$; **Significant difference $p < 0.01$

Table 5.4

Descriptive data and differences for successful and unsuccessful handballs within accurate and inaccurate groups

	Successful Mean ± *s*	Unsuccessful Mean ± *s*	Mean diff	95% Confidence Lower	Upper	*d*
Accurate group						
Joint angle at ball contact (°)						
Shoulder angle	19.14 ± 5.84	21.00 ± 6.73	-1.86	-3.89	0.17	0.54
Inaccurate group						
Distances						
Step-length (m)	1.01 ± 0.12	0.96 ± 0.13	0.05	-0.005	0.10	0.53
Step-length (% height)	55% ± 6%	52% ± 6%	3%	0%	6%	0.57
Resultant linear velocity at ball contact (m/s)						
Striking arm shoulder speed	1.62 ± 0.50	1.48 ± 0.43	0.15	0.01	0.28	0.32*
Direction (vector path, °)						
Step-angle	2 ± 3	0 ± 4	2	-0.2	4	0.76
Lower-trunk path	11 ± 10	9 ± 5	3	-4	9	0.53
Range of motion (°)						
Lower-trunk ROM	13 ± 7	11 ± 6	3	1	5	0.41*
Upper-trunk ROM	17 ± 4	15 ± 3	2	1	4	0.55*
Maximum angular velocity (°/s)						
Lower-trunk rotation velocity	144 ± 54	124 ± 47	20	0.4	39	0.39*

*Significant difference $p < 0.05$; **Significant difference $p < 0.01$

Pearson's correlations for parameters with $r > 0.4$ are provided in Table 5.5. Elbow angular velocity at ball contact was not entered into the CCA because of its strong correlation with maximum elbow angular velocity ($r = 0.98$). Canonical correlation analysis of the four remaining parameters indicated that the support hand mediolateral position contributed the least to the model and was therefore withdrawn. Thus, hand path, elbow ROM and maximum elbow angular velocity were considered for the final CCA.

Table 5.5

Pearson's correlations

	Accuracy		Hand speed	
	r	*p*	*r*	*p*
Hand path	-0.56	0.020	-0.01	0.980
Elbow ROM	0.45	0.059	-0.46	0.056
Maximum elbow angular velocity	-0.44	0.066	0.66	0.003
Elbow angular velocity (at ball contact)	-0.44	0.070	0.63	0.005
Support hand mediolateral position	0.42	0.085	0.13	0.614

The full canonical model was significant (Wilks $\lambda = 0.267$, $p = 0.009$) and explained 73% of the variance shared between the variable sets (large effect, $r = 0.85$, Cohen, 1988). Function one explained 60% of the variance between the variable sets and was statistically significant ($r_c^2 = 0.60$, $p = 0.009$). Function two explained 33% ($r_c^2 = 0.33$, $p = 0.074$) after extraction of the first function. While this function was not significant, $r_c = 0.57$ was above the selected cut-off of $r_c > 0.3$.

Standardised canonical function coefficients and structure coefficients for both functions are presented in Table 5.6. Communality coefficients indicate that maximum elbow angular velocity was the most useful variable in the model (Sherry & Henson, 2005).

Table 5.6

Canonical solution for Functions 1 and 2

	Function 1			Function 2			
Variable	Coef	r_s	r_s^2 (%)	Coef	r_s	r_s^2 (%)	h^2 (%)
Accuracy	-0.560	<u>-0.706</u>	49.87	0.853	<u>0.708</u>	50.12	99.9997
Hand speed	0.723	<u>0.836</u>	69.87	0.721	<u>0.549</u>	30.13	99.9998
Hand path	0.303	0.397	15.73	-0.877	<u>-0.837</u>	69.99	85.72
Elbow ROM	-0.040	<u>-0.767</u>	58.85	0.656	0.017	0.03	58.88
Maximum elbow angular velocity	0.891	<u>0.953</u>	90.86	0.893	0.285	8.14	99.01

Note. Structure coefficients (r_s) > 0.45 are underlined. Communality coefficients (h^2) greater than 45% are underlined. Coef = standardized canonical function coefficient; r_s = structure coefficient; r_s^2 = squared structure coefficient; h^2 = communality coefficient.

5.4 Discussion

Handball accuracy and the collective performance of accuracy and potential speed of ball travel have not been assessed in elite Australian football players. The aims of this research were to discriminate kinematics between accurate and inaccurate handballers, between successful and unsuccessful handballs and to address the kinematics related to the combined outcome of accuracy and hand speed.

Significant kinematic differences existed between accurate and inaccurate handballers. The accurate group exhibited a slower elbow angular velocity (both maximum and at ball contact), a smaller elbow ROM and a more direct hand path at ball contact in comparison with the inaccurate group. Reduced ROM is said to be more effective for submaximal high accuracy movements (Knudson, 2007). A smaller elbow ROM was associated with less angular velocity (analysed *post-hoc*, Figure 5.3), which is in agreement with the fundamental link between joint velocity and ROM (Knudson, 2007). Decreased elbow ROM and angular velocity may be indicative of a strategy by players to stabilise the movement and provide increased control of the hand for ball contact through constraining the number of joints acting in the system. This would represent a task dependent freezing of the redundant degrees of freedom (Ko, Challis, & Newell, 2003).

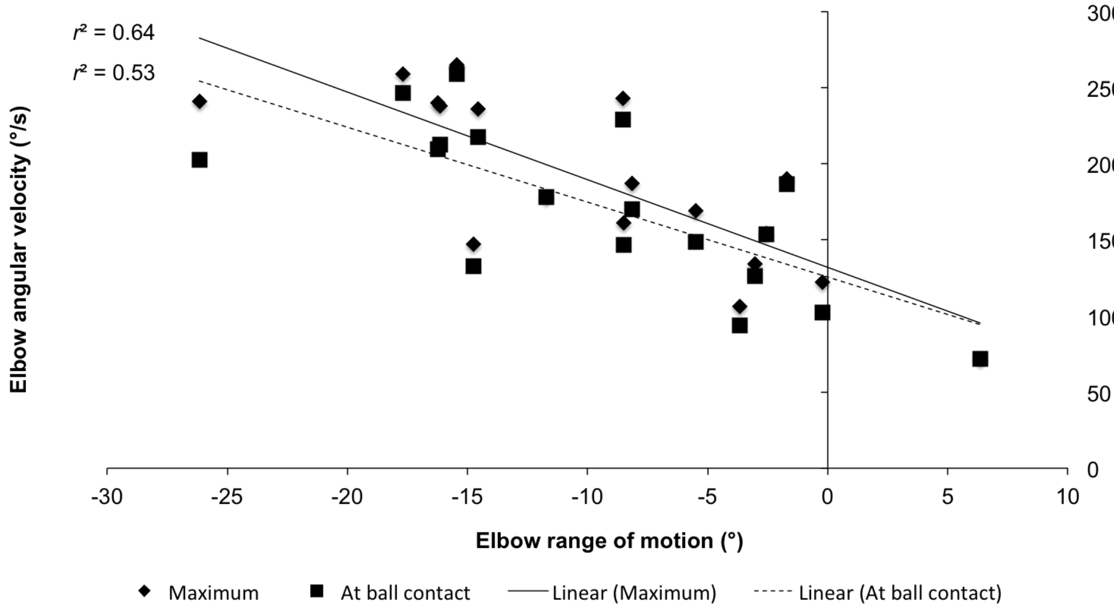


Figure 5.3: Relationship between elbow ROM and angular velocity.

Yang and Scholz (2005) suggested strategic development in controlling the degrees of freedom, such that the coordination of available degrees of freedom is characterised by the performers attempt to stabilise the performance outcome, rather than the concept of releasing degrees of freedom that evolves through practice (Vereijken, van Emmerik, Whiting, & Newell, 1992).

The smaller hand path angle at ball contact in the accurate group reflects a more direct line of contact in comparison with the inaccurate group. It is logical that a straighter, more direct hand path was found in the accurate group, as the line of force would therefore be propelling toward the target. This finding supports the coaching cue to “strike through the ball in the direction of the target” and the findings of Parrington et al. (2012).

Significant kinematic differences were also found between successful and unsuccessful handballs. Successful handballs exhibited a greater upper- and lower-trunk ROM and lower-trunk rotation velocity, a larger step-angle and a smaller elbow ROM in comparison with unsuccessful handballs. The greater trunk ROM and faster lower-trunk rotation velocity in the successful handballs may indicate an attempt to drive the movement through the proximal segments while controlling for arm related movements (i.e. as indicated by reduced elbow ROM). In other words, hand speed in the accurate handballs may occur through a better transfer of energy from the trunk, rather than a forceful development of angular velocity at the shoulder and elbow, which may affect the control of the point of contact of the hand.

The smaller elbow ROM in the successful handballs in comparison with the unsuccessful handballs is in agreement with previous Australian football handballing literature (Parrington et al., 2012). In addition, the fact that the accurate group was characterised by a smaller elbow ROM than the inaccurate group, provides strong support for it as an important factor for handballing accuracy. The greater step-angle in the successful handballs indicated a wider step that was more forward, as opposed to stepping across the line of the back foot, which would be implied by a smaller angle. This stance may be linked to the increased lower-trunk ROM (r = 0.53, analysed *post-hoc*) that is present in the successful handballs. Given the feet were planted, stepping forward as opposed to across the front of the body allows the lower-trunk to rotate more about the vertical axis, before getting to the end of internal rotation range of the front thigh. It could be hypothesised that this would ultimately link in to the player being “more square” to the target, which has implied importance through coaching and accuracy of passing (Parrington et al., 2012).

The inaccurate group presented a number of parameters that were significantly different between successful and unsuccessful handballs, while there were no significant differences found for the accurate group in the within-group analysis. These findings suggest that the inaccurate group were more variable in their technique between when they hit or missed the target. Peak movement variability occurs at around 60% throwing velocity and is suggested to decrease after this point (Urbin et al., 2012). Urbin et al. (2012) found that unskilled throwers actually exhibited less variability than skilled subjects when throwing at lower velocities. However, when they threw at 90% of maximum and 100% of maximum throwing velocity, their variability increased. Hand speed measured for the inaccurate group was 90% of hand speed found for maximal handballing. In contrast, hand speed for the accurate group was 83%, a comparable finding to van den Tillaar and Ettema (2003a), who found high performance players released the ball at 85% of maximum velocity when accuracy was the goal of the task. It is plausible that the accurate group had implicitly settled at 83% of maximum and that this was optimal for the distance and accuracy required (van den Tillaar & Ettema, 2003b), while the inaccurate group may have been trying to execute the skill with too much velocity.

Significant differences and effect sizes indicated that all linear and angular velocities were smaller in the accurate group in comparison with the inaccurate group. Linear and angular velocities were also decreased as a percentage of values found for maximal handballing; for example shoulder angular velocity was 78% and 87% of shoulder angular velocity found in maximal condition handballing for accurate and inaccurate groups, respectively (tested as part of a broader study). These findings indicate that slower movement speeds were associated with more accurate handballing performance and are in support of the speed-accuracy trade-off found in overarm throwing (Sachlikidis & Salter, 2007). In comparison, differences between successful and unsuccessful handballs indicated increased accuracy (successful handballs) was associated with increased velocity of movement, which may be related to reduced movement variability (i.e. impulse-variability theory, Urbin et al., 2011). Notably, while decreases in velocity have been found for elite overarm throwing when accuracy was the primary focus of the task, researchers also noted that accuracy did not improve, but rather tended to become more accurate as participants threw faster (van den Tillaar and Ettema, 2003a). Urbin et al. (2012) specify that the spatial error of a trajectory is not exclusively associated with the magnitude of force produced throughout the multi-joint movement and can be influenced by the preparatory position and orientation of body segments. An example of this is the mediolateral support hand distance from the lower-trunk, which is closer in both the accurate group and in the successful handballs. Although these kinematic factors are technique related, they are believed to act somewhat independently of velocity (force) generation (Urbin et al., 2012).

In order to establish important technical aspects for handballing where both accuracy and speed are required, a canonical correlation was performed to assess the multivariate relationship between predictor and performance variable sets. The full canonical model explained 73% of the variance between the variable sets, indicating a strong relationship between the composite performance and hand path, elbow ROM and maximum elbow angular velocity. Further interpretation and understanding of the relationships between these variable sets required assessment of the canonical functions (i.e. correlations between the variable sets).

The first canonical function explained 60% of the variance between the variable sets. The structure coefficients show an inverse relationship between hand velocity and score in function one, indicating faster hand speeds were associated with lower accuracy and vice-versa. The relationship between these two dependent variables demonstrates characteristics representative of the trade-off between speed and accuracy (Sachlikidis & Salter, 2007) and may be indicative of decreased contact (release) velocity as a result of accuracy emphasis (van den Tillaar & Ettema, 2003b). Structure coefficients of the covariates show a high contribution from maximum elbow angular velocity and elbow ROM and a lower contribution from hand path. The relationship between these indicated that increasing elbow ROM (negative sign due to elbow flexion) and increasing elbow angular velocity is associated with increased hand path angle, or a less direct striking line associated with less accuracy. This suggests that smaller elbow ROM and elbow angular velocity are linked with a more direct line to the target and consequently, accuracy.

The second function explains 33% of the remaining variance after the first function has been extracted. As the second function is responsible for explaining the maximum relationship between the variable sets not accounted for in the first function, the residual variance, the canonical correlation value is smaller. However, interpretation is still warranted because of the high squared canonical correlation value (Hair et al., 1998). Hand path is the primary contributor of the covariates in the second function, exhibiting the highest squared structure coefficient (70%), while elbow angular velocity contributes slightly (8%) and elbow ROM less than 1%. Hand path is inversely related to hand speed and accuracy, indicative that a less angled strike path is associated with greater hand speeds and accuracy. Fundamentally, a less angled striking force travelling through the ball toward the target would propel the ball with minimum mediolateral velocity or lateral torque, thereby reducing deviation from the centre of the target (Knudson, 2007). If this is the case, accuracy may not be as adversely affected through the increase of hand speed when the hand path is directed toward the target, rather there is positive association.

The canonical model suggests that the speed-accuracy trade-off and the impulse-variability theory may not be mutually exclusive. Function one demonstrates a decrease in accuracy linked with increased velocity, associated with an angled hand path. The remaining variance explained by function two indicates that with a more direct hand path, faster hand speeds and accuracy are linked. Variance unexplained could be related to hand-to-ball interaction. The ovoid shape of the ball means that contact on different parts of the ball circumference would be at different distances from the ball geometric centre, which could cause oblique spin about the balls short or long axis. Both ball orientation and the nature of impact between the ball and the foot have been considered as important factors for punt kicking with ovoid shaped balls (Ball, 2008; Ball, 2011a).

This study presented information from three methodological approaches: accurate-inaccurate group differences, successful-unsuccessful handball differences and canonical correlation analysis. Though parameters may be significant across each method of analysis (e. g. elbow ROM), it is logical that some parameters only discriminate one style of analysis. Dichiera et al. (2006) suggested using successful versus unsuccessful trials as it allows participants to be used as their own controls. This method also provides technical information to accurate players where accurate-inaccurate group analysis would not. Canonical correlation analysis allowed the assessment of multiple dependent performance variables, which has been viewed as important in throwing and striking skills (van den Tillaar & Ettema, 2003a; 2003b). The holistic approach taken in this study provides coaches with information to help improve technique in inaccurate handballers as well as improving individual technique in those who are already accurate.

The use of hand speed as a surrogate measure for ball speed was a limitation in this study. This limitation was based on the assumption of a linear correlation between the speed of the striking segment and the ball speed, which has been shown to occur in Australian football kicking (Ball, 2008). Another limitation included the lack of ability to cross-validate the handballing task. Player skill ratings from coaching staff at the football clubs would have provided the ability to validate accuracy score per player against the coaches' skill rating of the player, however, these data were not collected. The collection of this information is recommended as a future consideration. In addition, coaches' assessments of players may take into account game performance, where other factors such as pressure or the complexity of the game environment may effect the execution of the handball.

Consequently, the findings of this paper stimulate a number of future directions. Handballs are performed under complex cognitive situations within the game with cues received both audibly and visually. Game-based handball analysis (Parrington et al., 2013b [Chapter 2 of this thesis]) has demonstrated 46% of passes are made under moderate to high pressure (tackle made during or immediately after handball) and 92% of passes are made in less than three seconds of receiving the ball. Examining technique under pressure and combined with decision-making conditions will contribute to the foundation of knowledge of this skill.

5.5 Conclusion

This study explored the kinematics of handballing in Australian football in relation to accuracy and a composite performance of accuracy and hand speed. Elbow angular velocity, elbow ROM and hand path were smaller in the accurate group in comparison with the inaccurate group. Elbow ROM was smaller in the successful handballs, while trunk motion (upper- and lower-trunk ROM and lower-trunk rotation velocity) and step-angle were greater in the successful handballs than in the unsuccessful. Shoulder linear velocity, lower- and upper-trunk ROM and lower-trunk rotation velocity were greater in the inaccurate group's successful handballs, while the accurate group revealed no significant differences between successful and unsuccessful handballs. Canonical correlation analysis revealed a strong relationship between elbow ROM, elbow angular velocity and hand path with accuracy and hand speed. Reducing elbow joint motion may assist the stabilisation of the arm movement for a controlled fist contact with the ball and greater accuracy. However, this may reduce possible ball contact speed. Striking the ball in a direction through to the target and stepping forward, rather than across the line of their back foot may help players to achieve a more accurate handball.

6 Study 5: How task complexity and stimulus modality affect motor execution: Target accuracy, response timing and hesitations.

(Adapted from: Parrington, L., MacMahon, C., & Ball, K. (In Press). How task complexity and stimulus modality affect motor execution. *Journal of Motor Behavior*.)

Elite sports players are characterised by the ability to produce successful outcomes while attending to changing environmental conditions. Few studies have assessed whether changes in the perceptual environment affect motor-skill execution. To test the effect of changing task complexity and stimulus conditions, we examined response times and target accuracy of twelve elite Australian football players using a passing-based laboratory test. Data were assessed using mixed modelling and chi-square analyses. No differences were found in target accuracy for changes in complexity or stimulus condition. Decision, movement and total disposal time increased with complexity and decision hesitations were greater when distractions were present. Decision, movement and disposal time were faster for auditory in comparison with visual signals, and when free to choose, players passed more frequently to auditory rather than visual targets.

These results provide perspective on how basic motor control processes such as reaction and response to stimuli are influenced in a complex motor skill. Findings suggest auditory stimuli should be included in decision-making studies and may be an important part of a 'decision-training' environment.

6.1 Introduction

During game-play, athletes are required to execute movements in response to complex situations. Part of the complexity of sport results from the variety of auditory and visual cues that signify potential options, or that may act to distract the athlete. These complex conditions demand the need for expertise in both cognitive (perceiving and interpreting) and motor-skill execution (functional response) components of tasks. Consequently, it has been proposed that a lack in either perceptual-cognitive or perceptual-motor skill constrains performance (Starkes et al., 2004).

Previous motor learning research has focussed predominantly on the cognitive aspects of performance (e.g. efficient processing, Fitts & Posner, 1967; automaticity, Beilock, Bertenthal, McCoy & Carr, 2004; Beilock, Carr, MacMahon, & Starkes, 2002). Even research that has attempted to include both cognitive and motor elements using in-situ designs has still focused on the explanation of cognitive information (e.g. decision making, Bruce et al., 2012; anticipation, Mann et al., 2010), rather than how physical behaviour is affected by any changes in perceptual conditions.

More recently, motor execution aspects of perceptual processing in performance have gained focus. A study conducted by Shim et al. (2005), for example, found no difference in anticipation accuracy for different levels of projected information but found shorter response delays in reaction to a live opponent in contrast to a ball projected from a ball machine. Similarly, Panchuk et al. (2013) used a coupled approach to look at dissociated visual and ball flight information. Panchuk et al. found that the absence of advanced perceptual information results in reduced skill performance and changes in catching kinematics (delayed movement initiation, faster velocity) as well as reduced visual tracking.

Given the general lack of research focus on the interaction between technical output and perceptual tasks, many questions remain to be answered. Chief among these is whether the cognitive difficultly of a decision problem influences the motor response. For example, the number of passing options, introduction of distractor stimuli, or the type of stimulus modality all present potential complexities that may exist in a game environment. These three task features were considered in this study to understand how decisions with varying levels of complexity influence performance of a motor skill.

In team sport decision making, where there are multiple options, Hick's Law is expected to play a subtle role in the outcome of performance. Hick's law states that as the number of equally likely response choices increase, reaction time will increase logarithmically (Hick, 1952). Therefore, as the number of potential options and the method of execution change during games, it is plausible that the response time will be affected. Response selection may also be affected by the availability of valid and invalid cues. For instance, additional information in the form of an invalid cue may cause a distraction that diverts the decision maker's attention away from their intended target. Because of attentional capacity limitations, the processing of distractions reduces available resources for the processing of task-relevant information (Janelle, Singer, & Williams, 1999). The distraction effects and total processing demands are believed to intensify under increased task complexity and an increased similarity of a distraction to a relevant cue (Graydon & Eysenck, 1989).

Notwithstanding the intuitive relevance, we know little about how motor skill performance changes under distraction due to different cues. Research conducted in the area of vehicular safety has provided empirical evidence of decreased driving performance under distraction. Studies using simulation have revealed that distracted drivers reduced driving headways (distance between vehicles), increased brake pressure (Lansdown, Brook-Carter, & Kersloot, 2004) and were less prepared to react to conditions (Horberry, Anderson, Regan, Triggs, & Brown, 2006). Drivers have also demonstrated longer response times, more misidentifications between valid and invalid stimuli, and greater saccadic and fixation activity to peripheral locations (Janelle et al., 1999). Similarly, studies have found that manoeuvring an actual vehicle whilst distracted results in slower braking initiation times, more intense braking and changes to braking distance (Hancock, Lesch, & Simmons, 2003; Hancock, Simmons, Hashemi, Howarth, & Ranney, 1999). Given the changes demonstrated in the timing and magnitude of the movement response, it is plausible that changes would occur for more complex motor tasks performed in the presence of distractions.

Another factor considered in this study is that the possible decision options during team games are not just signalled by visual stimuli, but also auditory stimuli. An example of this could be the difference between a teammate making a run for the ball or waving versus verbally calling for the ball. At any point during option selection there may be a combination of visual and auditory signals. Previous decision-making study designs have focussed their examinations on visual cues and have not used auditory cues. This lack of acoustic or bimodal focus may stem from findings of the visual dominance effect (Colavita, 1974), whereby responses to visual stimuli have been found to dominate over acoustic stimuli from spatiotemporally similar bimodal targets (Koppen & Spence, 2007a; 2007b). Nevertheless, acoustic information is available from the competition environment, which may not always emanate from the same location. It is therefore relevant to assess auditory stimuli as potentially salient cue providers, especially given auditory signals can capture attention regardless of visual focus (Petocz, Keller, & Stevens, 2008; Szalma et al. 2004).

Response to visual and auditory stimuli has been measured in seated laboratory conditions, however, it is yet to be assessed within the sport domain. Factors such as different head movement strategies for auditory and visually evoked responses (Goossens & Van Opstal, 1997), differences in saccadic response (latency and accuracy) between visual and auditory targets presented at different eccentricities from the starting focal position (Yao & Peck, 1997), and sound localisation errors in the presence of acoustic distraction(s) (Langendijk et al., 2001) may influence the participants' perceptual-motor execution.

The call for more realistic simulations to increase ecological validity (e.g. Starkes et al., 2004) of sport decision-making research has influenced researchers to formulate study designs that increase game-like fidelity. These have included movement responses to life-size projected displays (Helsen & Pauwels, 1993), in-situ anticipatory movement responses under temporal occlusion (Müller & Abernethy, 2006; Müller et al., 2009; Mann et al., 2010), in-situ game scenario simulations (Bruce et al., 2012; Shim et al., 2005) and above real time video simulation training (Lorains et al., 2013a; Lorains et al., 2013b). These designs have focussed on understanding particular components of performance. For example, Lorains et al. (2013a; 2013b) focused on the component of video speed and how this affected decision-making performance. In comparison, Mann et al. (2010) focused on how undertaking movement contributed to anticipatory skill. Information on the differences in response to visual and auditory stimuli may provide evidence for the inclusion of both in future designs.

Understanding how athletes respond to changes in task complexity, the presence of distractors and with variations in target stimulus modality has implications for the methodology of future decision-making research, as well as the training of decision making for sports and other applied areas. As a result, in this study, we aimed to answer three questions: (a) what is the effect of task complexity on absolute target accuracy and decision-response parameters? (b) Do absolute target accuracy or decision-response parameters change as a result of the type of stimulus provided to the athlete (auditory versus visual)? (c) Do players respond more frequently to auditory or visual stimuli when both are present?

Due to the current state of the literature and our goal to assess effective decision making and functional skill execution, this study examined Australian football handballing in a novel laboratory-based test. Handballing is a passing manoeuvre performed often under moderate and high levels of pressure, which uses the clenched fist of one hand to strike the ball out of the other hand (Parrington et al., 2013 [Chapter 2 of this thesis]).

We hypothesised that increasing task complexity would adversely affect the accuracy and timing performance of the handball. We also hypothesised that when confronted with two valid competing stimuli, one auditory and one visual, players would be more challenged than when only one valid option was provided against a distractor. We had no clear expectations on how auditory and visual stimuli would influence performance.

6.2 Methods

6.2.1 Participants

Twelve elite male football players (20.2 ± 2.2 years, 85.8 ± 8.2 kg, 1.89 ± 0.09 m), contracted to one professional Australian Football League (AFL) club participated in this study. All participants were currently taking part in pre-season or in-season training at the time of testing. No baseline visual acuity or hearing tests were undertaken. Participants provided informed consent prior to testing and the University Human Research Ethics Committee approved all research.

6.2.2 Equipment

Five bulls-eye targets were created with a central circle of 0.2 m diameter, positioned 1.5 m high. Targets were set in a star formation, five meters each from the central starting position, with the centre of each target 72° apart, such that the participant had a single target in front and equally spaced targets at the front left and right and back left and right to form a 360° testing environment.

The central circle of each target was composed of an interchangeable blue/ red illuminating panel, which corresponded to relevant primary colours of the players' team strip (Figure 6.1). These colours were chosen in an attempt to make the visual stimuli more meaningful to the participant. Directly below this sat a 6-inch speaker that was able to emit varying recorded sound files (#.wav) files. Two specific auditory signals (#.wav files) were created; the call "here" and the call "no" were recorded as typically called out in a game via microphone. The files were digitally manipulated such that both auditory signals were set at the same decibel level and onset time was equivalent for both signals (Mixcraft, Acoustica, Inc., Oakhurst, CA, USA).

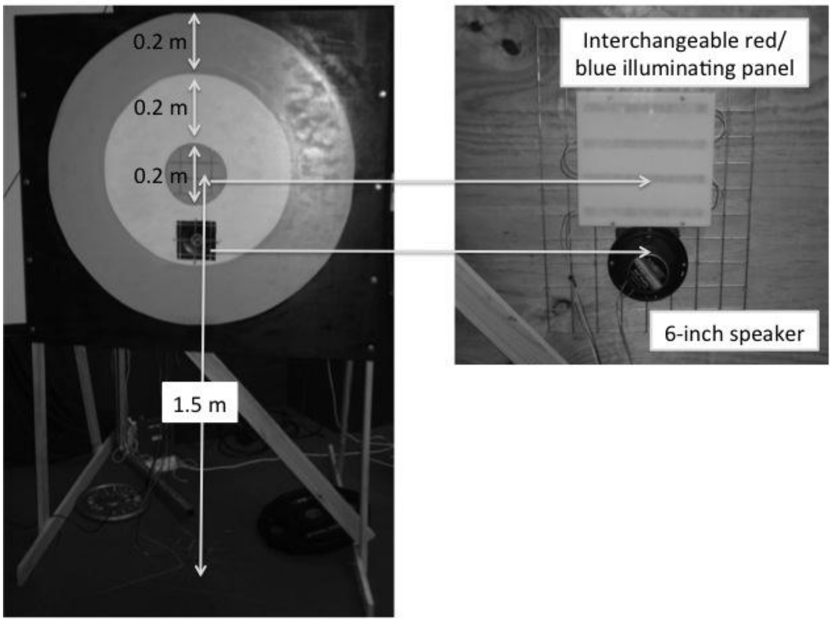


Figure 6.1: Targets used during testing.

Each target had the ability to emit one of either visual or auditory signals at a given time. Signal emission was controlled via a LabView interface (National Instruments Corporation, Austin, TX, USA), specifically created for the purpose of the project. Pilot testing was conducted to understand discrimination between timing for auditory and visual stimulus presentations at a five metre distance. The onset of signals between 150 ms auditory leading to 150 ms visual leading was tested to identify the delay period between which the onset of both signals could not be discriminated (King, 2005), to be used for testing. This method helped avoid issues related to temporal asynchrony between the auditory and visual signals.

6.2.3 Task design

Testing procedures for the handball targeting task included five levels of intended incremental complexity. Complexity was added through increasing the number of target options, and including distraction signals (of either the same or different stimulus modality). Level five was a ‘free choice’ condition, which had two primary purposes: the first was to assess whether having two competing valid options would increase decision time because of increased choice; and the second was to assess player preference for auditory or visual targets. Excluding level one, the targets were assigned such that the location appeared random to the participant, but were selected in a manner that each target would only be hit once by handballs from the preferred and non-preferred hand once each. False trials were introduced throughout the test in order to reduce any chances of players anticipating the next trials target location.

6.2.4 Protocol

Each participant completed a warm up on either a cycle ergometer or treadmill at a self-selected pace between 50-70% effort. Following this, participants performed at least five handballs on both the preferred and non-preferred hand to become familiar with the testing environment and equipment. Each participant then completed a total of 80 handballs, across five different testing difficulty levels (1-SR to 5-CRO, described in Table 6.1). The protocol for the four difficulty levels required the first half of the trials per level to be performed with the preferred (or non-preferred) hand. This was embedded in the protocol to ensure that each participant hit the required targets once with both preferred and non-preferred hand. In level five participants were able to use whichever hand they desired.

The starting position per trial required players to stand in the centre of the five targets, with their chest facing the frontal target. The football was positioned at the feet, and participants were required to stand with their head down and eyes focussed on the ball until the pre-stimulus cue was provided. The cue "ready, go" was provided by the researcher controlling the stimuli settings, who subjectively differed the time between the two words in order to reduce the chance of anticipation by players.

A two-minute break was allowed between each testing level, where the specific test requirements were reiterated to the participant. For each handball trial, participants were required to hit the target signalling the appropriate stimulus, as defined for that level. Players were asked to perform with 'game-intensity' and informed that they were being tested for both accuracy and response time.

Table 6.1

Breakdown of task

Complexity level	Trials	Target stimulus	Distractor stimulus	Possible correct response (invalid distractor stimulus/stimuli)
Level 1 (1-SR): Simple response	16	Auditory Visual	None	Single target only
Level 2 (2-CR): Choice response	20	Auditory Visual	None	One out of five targets
Level 3 (3-CRD): Choice response with same-modality distractor	20	Auditory Visual	Auditory Visual	One out of five targets (one distractor from any remaining target)
Level 4 (4-CRDX): Choice response with cross-modality distractor	12	Auditory Visual	Visual Auditory	One out of five targets (one distractor from any remaining targets). Instructed which stimulus modality to go to.
Level 5 (5-CRO): Free choice response with option between two valid options	12	Auditory or visual Players instructed to go to whichever target they preferred		One out of five targets emitted auditory target signal, any remaining target emitting the visual target stimulus.

Motor skill execution was assessed through absolute target accuracy, based on a 3-2-1-0 rating, according to where the ball contacted the concentric rings (refer to Figure 6.1). Accuracy was manually recorded and then reviewed using two-dimensional video. All testing was completed using an official AFL competition ball (Sherrin, Russell Corporation, Melbourne, inflated pressure 69 kPa).

6.2.5 Data analysis

To assess the effect of task complexity on absolute target accuracy and decision-response parameters (Table 6.2), each parameter was analysed separately using a linear mixed-model analysis conducted in SPSS 20.0 (IBM Corporation, Armonk, NY). The mixed approach has the benefit of accounting for unbalanced data and the ability to assess different covariance structures for random errors and random effects (West, 2009). For each model, a combination of fixed-factor (task-difficulty, target-location) and random-factor (participant) were assessed. A maximum likelihood estimation method was used, as it is believed to be a better approach when fixed factors are of primary interest (Twisk, 2006).

Table 6.2

Parameter definitions

Parameter	**Definition**
Absolute accuracy score	3-2-1-0 scale based on bull's-eye target
Initiation time	Time from pre-stimulus cue to ball possession
Decision time	Time from ball possession to ball contact
Movement time	Time from stimulus onset to ball contact
Disposal time	Time from onset of stimulus to when the ball has connected with the target
Decision hesitation	Pause or fault in movement in order to correct decision
Technical hesitation	Pause or fault in movement in order to correct technique

Briefly, graphical exploratory data analyses were conducted to assess which covariance matrix would best fit the model. Model adequacy was assessed via penalised likelihood approach using the Bayesian information criterion (BIC), which calculates the likelihood of the observed data within the model and a Likelihood ratio test to test the goodness of fit between models. Significant effects (for difficulty level) were assessed further using a *post-hoc* Bonferroni correction. This process was repeated for stimulus modality. Chi-square analysis was used to assess whether players attended to auditory or visual cues more frequently and assess the frequency of preferred arm use.

6.3 Results

6.3.1 Task complexity

Absolute accuracy score and initiation time were not significantly affected by task difficulty. Decision time was significantly affected by task difficulty, $F(4, 66.174) = 13.838$, $p < 0.001$. Decision time was faster in 1-SR ($M = 0.573$) in comparison with 2-CR ($M = 0.808$, $p < 0.001$), 3-CRD ($M = 0.804$, $p < 0.001$) and 4-CRDX ($M = 0.786$, $p < 0.001$). The choice response with optional modality selection (5- CRO) ($M = 0.638$) was not different to 1-SR, but was faster than 2-CR ($p = 0.001$), 3-CRD ($p = 0.002$) and 4-CRDX ($p = 0.014$). Movement time was significantly affected by task difficulty, $F(4,884.144) = 44.577$, $p < 0.001$. Participants moved faster to make the handball in 1-SR ($M = 0.893$) and 5-CRO ($M = 0.993$) ($p < 0.001$), but there were no differences between 2-CR ($M = 1.189$), 3-CRD ($M = 1.226$) and 4-CRDX ($M = 1.236$). There was no significant difference between 1-SR and 5-CRO ($p = 0.064$). Disposal time was significantly affected by task difficulty, $F(4, 882.116) = 37.095$, $p < 0.001$. Disposal time was faster in 1-SR ($M = 1.448$) and 5-CRO ($M = 1.491$) in comparison with 2-CR ($M = 1.704$), 3-CRD ($M = 1.748$) and 4-CRDX ($M = 1.780$), $p < 0.001$. No differences were found between 1-SR and 5-CRO, or between 2-CR, 3-CRD and 4-CRDX.

Decision hesitations were significantly affected by task difficulty, $F(4, 936.00) = 8.085$, $p < 0.001$. The simple response task ($M < 0.0001$) had significantly fewer decision hesitations than 3-CRD ($M = 0.088$, $p = 0.002$) and 4-CRDX ($M = 0.139$, $p < 0.001$), but not different to 2-CR ($M = 0.058$) or 5-CRO ($M = 0.033$). There were no significant fixed effects for technical hesitation for task difficulty, $F(4, 281.952) = 2.013$, $p = 0.093$.

6.3.2 Stimulus modality

No effects were found for absolute accuracy or initiation time. Decision time was significantly affected by stimulus type, $F(1, 37.997) = 37.997$, $p < 0.001$, with decision time significantly faster when responding to auditory stimuli ($M = 0.748$) in contrast to responses to visual stimuli ($M = 0.847$). Movement time was also significantly affected by stimulus type, $F(1,29.908) = 10.059$, $p = 0.003$, with movement time faster to auditory stimuli ($M = 1.054$) than to visual stimuli ($M = 1.206$). Disposal time followed the same trend and was significantly affected by stimulus type, $F(1, 29.092) = 8.064$, $p = 0.008$, with disposal time significantly faster when responding to auditory stimuli ($M = 1.580$) in comparison with visual stimuli ($M = 1.734$). Significantly more decision based hesitations occurred in response to visual stimuli ($M = 0.087$) compared with auditory stimuli ($M = 0.041$), $F(1, 932.00) = 8.278$, $p = 0.004$, while stimulus modality did not effect technical hesitation. The descriptive data for each difficulty level for the different stimulus modality conditions are presented in Table 6.3.

Finally, when both auditory and visual valid target options were presented in the free choice response condition (5-CRO), players more frequently chose to handball to the auditory target in comparison with the visual target $\chi^2(1) = 7.188$, $p = 0.007$.

Table 6.3

Comparison of absolute accuracy score, response time variables and hesitations for visual and auditory responses at each difficulty level

		1-SR		2-CR		3-CRD		4-CRDX		5-CRO	
		Auditory	Visual	Auditory	Visual	Auditory	Visual	Auditory	Visual	Auditory	Visual
Absolute accuracy score	M	1.59	1.72	1.80	1.80	1.84	1.86	1.81	1.74	1.75	1.93
	SD	0.72	0.74	0.76	0.73	0.74	0.75	0.70	0.78	0.74	0.75
Initiation time (s)	M	0.337	0.307	0.296	0.330	0.318	0.300	0.270	0.354	0.289	0.324
	SD	0.241	0.250	0.204	0.205	0.239	0.198	0.216	0.179	0.186	0.165
Decision time (s)	M	0.568	0.574	0.784	0.969	0.849	0.980	0.821	1.047	0.694	0.674
	SD	0.190	0.175	0.245	0.409	0.308	0.426	0.316	0.521	0.203	0.249
Movement time (s)	M	0.908	0.874	1.080	1.301	1.170	1.289	1.083	1.401	0.983	0.998
	SD	0.263	0.292	0.251	0.379	0.285	0.398	0.355	0.496	0.237	0.248
Disposal time (s)	M	1.479	1.415	1.594	1.817	1.694	1.806	1.613	1.960	1.474	1.505
	SD	0.316	0.352	0.274	0.398	0.316	0.416	0.366	0.538	0.263	0.270

6.3.3 *Post-hoc* analyses

Effect sizes (Cohen's *d*, Cohen, 1988) were analysed *post-hoc.* Decision time, movement time and disposal time were all shorter in response to auditory stimuli in the presence of a visual distractor in comparison with attending to a visual target in the presence of an auditory distractor (d = 0.53, d = 0.74, d = 0.75, respectively). In addition, variability was greater for visual responses in the presence of auditory distractions found in the cross modality distractor condition (Figure 6.2).

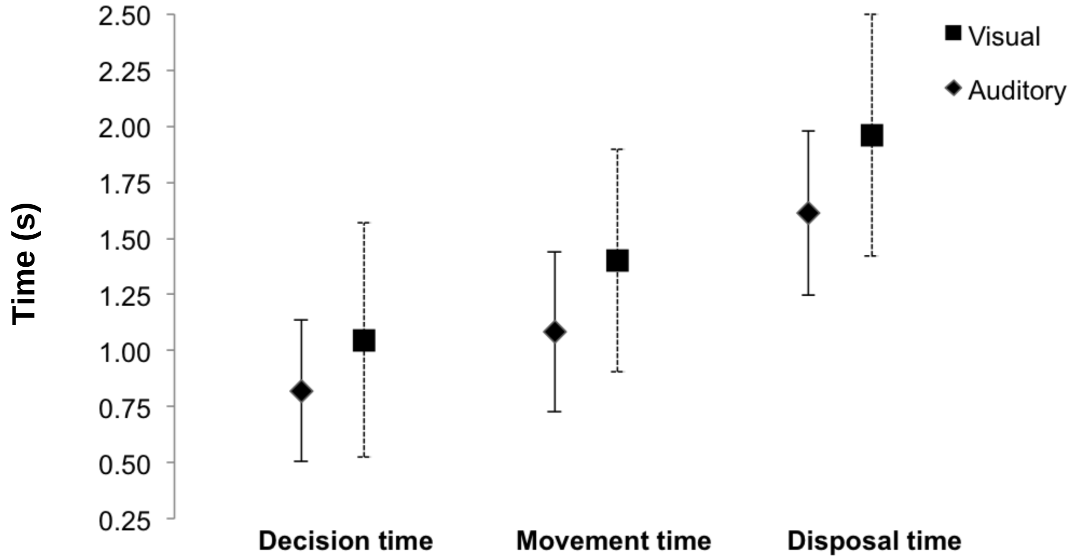


Figure 6.2: Cross-modality condition (L4): Decision, movement and disposal time for auditory and visual signals.

A negative effect of cross-modality distraction for visual stimuli and a positive effect for auditory stimuli were found. Initiation time for attending visual stimuli was slower when auditory stimuli acted as a distractor (cross-modality) in comparison with a visual distractor (d = 0.29). In comparison, movement to an auditory target in the cross-modality condition was faster than when an auditory stimulus acted as a distractor (d = 0.21). This finding was replicated in movement time (visual, d = 0.25, auditory d = 0.27) and disposal time (visual, d = 0.32, auditory, d = 0.26), while no effects were found for decision time. This effect is illustrated in Figure 6.3, showing the movement time measure of auditory and visual conditions.

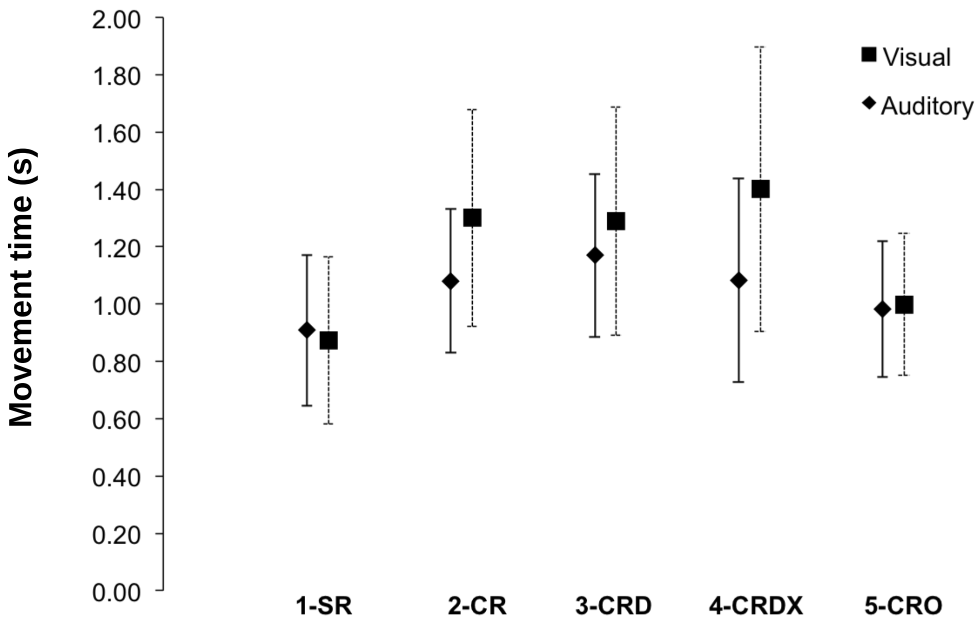


Figure 6.3: Movement time per level for auditory and visual signals.

6.4 Discussion

This study assessed Australian football players' handballing target accuracy and decision based timing parameters in response to changes in task complexity and stimulus modality. We also assessed whether players attended more frequently to auditory or visual cues.

Our findings suggest that cognitive loading has a greater effect on the decision components (response-timing parameters) than on the skill execution components of handballing. Specifically, decision time, movement time, and total disposal time increased when there was an increase in options and distractors present, with the longest mean response times occurring in the cross-modality distractor condition, when there was a choice of responses and auditory and visual modalities were competing. The increase in response time parameters (decision, movement, and disposal), coinciding with an increased number of options and/or information to attend to is demonstrative of Hick's Law (Hick, 1952) in a complex multi-segment coordinated movement. The findings from this study did not replicate the logarithmic increase in response time as indicated in Hick's equation, nevertheless, the increased complexity of the task required a greater period of time by the players to observe and interpret the testing environment and select a response prior to performing the appropriate action.

A novel aspect to the design was the inclusion of distractor cues. The results suggest that when distractors in the form of an invalid cue were present, participants may have diverted or shifted attention from the primary intended target, causing a longer time to respond. This is evidenced by slower response times (decision, movement and disposal) in the two distractor conditions in comparison with the free choice condition. In each of these levels, both auditory and visual stimuli were presented, however, in the distractor conditions, participants were instructed to attend only to the valid stimuli and ignore the invalid stimuli provided as a distraction. In comparison, in the free choice condition participants were free to choose which modality they handballed to (two valid cues). Similar findings, such as longer response times (Janelle et al., 1999) and slower braking initiation times (Hancock et al., 1999; Hancock et al., 2003) have been shown in vehicular driving research in the presence of distractors. Decision hesitations, considered to be a pause or fault in the movement in order to correct the selection of target, occurred in both distractor conditions. The presence of decision hesitations reflects decreased certainty of participants' decision in the presence of distractor signals. The results may represent a shift in focus between competing target options, followed by acknowledgement and elimination of the incorrect stimulus. Visual search information, in future work, could be used to confirm this focus shifting supposition.

That there were no differences in response timing parameters between the simple response task and the free choice task was unexpected. Our hypothesis was that when confronted with two valid competing stimuli, one auditory and one visual, players would be more challenged than when only one valid option was provided against a distraction. We anticipated that this condition would have a greater degree of uncertainty and that players would need to make a choice between the two available valid target options. Rather, movement, decision and disposal time to visual or auditory signals in the free choice task were no different to response times in the simple response task. The faster decision-response times in this condition may have been a result of the fact that in free choice task, two valid cues were presented from targets for participants to handball to. Thus, in line with Hick's Law, the additional valid target option created an easier choice response task (two out of five, rather than one out of five). Players may have found the task less complex due to presentation of more potential options, which reduced the need to search for as much information prior to decision selection, allowing less attention-demanding processing (Fitts & Posner, 1967). Again, investigating the visual search patterns of players in future research would allow this information to be provided.

A main finding of this study is that timing measures changed with increased cognitive load, although target accuracy did not. In this task, participants were instructed to respond accurately in a 'game-like' fashion and informed they were being assessed on both timing and technical accuracy, however, accuracy may have been prioritised over the time taken to perform the handball, in a speed-accuracy trade off (Fitts, 1954). Movement accuracy is believed to play a role in reaction time, with increasing accuracy demands for a movement increasing the amount of preparation time required (Magill, 2007). In Australian football players may remain in possession of the ball for any length of time and are only penalized for holding on to the ball once legally tackled or if the player fails to bounce the football at least once every 15 metres (AFL, 2014). The findings of Study 1 (Parrington et al., 2013 [Chapter 2 of this thesis]) demonstrated that longer disposal times were not an indicator of decreased passing efficiency and that players were able to make successful passes, which maintained team ball possession regardless of time constraint or time to perceive the environment. Thus, as task complexity increased, the participants may have placed greater emphasis on mechanical proficiency to ensure a successful and more accurate handball pass to the correct target, which may have resulted in them taking more time. One caveat here is that during games, there is a limit to the length of time a player can remain free prior to being tackled. Future work could assess the theory of prioritisation of skill execution and accuracy over speed in a motor skill where accuracy is valued over response speed.

Increased cognitive load did not affect the number of technical hesitations. Together with the lack of effect of cognitive load on target accuracy, this indicates that the skill was executed functionally despite the increased number of options and the presence of distractor signals. Similarly, accuracy and technical hesitations were not affected by stimulus modality. It is plausible that changes within our design to modify the cognitive task difficulty effected the perceptual processing more so than the movement execution and technical aspects of the skill. It is also possible that the biomechanical responses of players did change, but that this detail requires the precision of kinematic analysis, which is recommended as a consideration for future research. Conversely, the lack of recognisable fault in skill execution measured here could be an outcome of testing a submaximal skill. Whether increased complexity elicits changes in the functional outcome of a more maximal motor skill is also an interesting step for future research.

Overall in this study, players' decision time, movement time and total disposal time were faster in response to auditory cues than the visual cues. Although participants were equally fast to respond to visual or auditory stimuli that were presented in front of the body in the simple response condition, analyses conducted *post-hoc* indicated a superiority of auditory over visual responses occurred during the choice-response and both choice-response with distraction conditions where players were required to attend to targets situated at any of the five positions about their body (front, front left/right, back left/right). Though this finding may seem quite fundamental, the results help to highlight that calling for the ball via an auditory signal when outside of the ball carriers line of vision may result in a quicker response and ball disposal. This suggestion may be further justified by findings that responses to auditory target stimuli presented at target eccentricities of 30° to the left or right of the initial focal location are faster than responses to visual stimuli (Yao & Peck, 1999). In addition to this, different head movement strategies have been detected for auditory-evoked and visually-evoked capture, with eye-head latency differences shown to be shorter in auditory-evoked responses (Goossens & Van Opstal, 1997).

Thus, part of the findings may have been due to study design as players were required to focus on the ball until the initial warning signal was emitted prior to stimulus onset. This procedure controlled the starting position between participants and reduced bias toward the frontal target. With this method, the visual stimulus was presented outside of the initial focal position and thus there was no opportunity to take advantage of the faster response to this modality when aiming at frontal targets (Yao & Peck, 1999). The findings provide insight to the potential contribution of acoustic information in sporting conditions. From a practical perspective, results suggest that, in a game environment, auditory cueing for the ball may provide a more detectable source of information in comparison with visual signalling, regardless of a player's body or head position (Petocz, Keller, & Stevens, 2008; Szalma et al. 2004). Furthermore, it is not harmful for players to provide an auditory call for the ball, as the ball carrier may respond equally as fast or faster to this cue.

Our data provide evidence to support the influence of auditory stimuli in decision response. In particular, this work suggests that auditory distraction may cause greater disruption to players than visual distraction. This is demonstrated by the negative effect of the auditory distraction on movement and disposal time in both matching and cross-modality distractor conditions, and comparatively the positive effect when aiming for auditory stimuli in the presence of a visual distraction. More simply, auditory signals trump visual signals. We also revealed through chi-square analysis of the free choice condition that participants handballed toward auditory stimuli more frequently than visual stimuli. Although no time differences were present for passing to an auditory versus visual cue when presented in isolation in the simple response task, players generally responded faster and more often to auditory stimuli throughout the remaining levels.

The results of this study may seem contradictory to the robust findings of the Colavita visual dominance effect, however, it is plausible that a number of task design features are responsible for the differences. Spatial separation between bimodal target locations has been shown to reduce the magnitude or remove the visual dominance effect (Koppen & Spence, 2007a; 2007b). As our design looked at two competing stimuli from spatially different targets, rather than one multisensory signal, it is not surprising that our results do not exhibit a visual dominance. Another relevant factor involves the starting position of the players, as players were required to look down prior to the stimulus pre-cue and when picking the ball up. Spence, Parise and Chen (2012) identified that participants would more likely respond to auditory events than visual events in instances where participants temporarily close their eyes or look away. Thus, under these task constraints, attention of the player may have been more easily captured by the auditory signal (Petocz, Keller, & Stevens, 2008; Szalma et al. 2004).

Our findings pose an interesting debate on the use of traditional decision-making paradigms in sport research, where the contribution of auditory signals has been a neglected component of research designs. Auditory signals appear to provide a vital cue and should be considered in future research. Nonetheless, though we have emphasized the importance of auditory cues, as revealed by this study, we acknowledge that stimulus-response compatibility may have influenced the findings that the auditory stimulus was chosen more often than the visual stimulus. In our testing protocol, the auditory signal was a recording of a peer calling “here”, in comparison with the visual signal, which was the centre of the target illuminating in the primary colour of the player’s team uniform. The auditory call may have provided greater compatibility and meaningfulness, resulting in faster reaction time (Magill, 2007).

To our knowledge, this is the first study to examine the effects of task complexity and responses to visual and auditory stimuli in a movement task. There is potential for future multidisciplinary research to explore whether kinematics change as a result of task complexity or stimulus modality. In addition, visual search patterns may provide insight into the effect of distractions and in scenarios where both visual and auditory stimuli are presented.

6.5 Conclusion

The purposes of this study were to evaluate the effects of changing task complexity, the influence of stimulus modality and the frequency with which participants passed to competing visual and auditory stimuli. A novel 360° stimulus-response design was developed to assess these factors in a movement-based task using elite Australian footballers. We found that players were slower with respect to movement, decision and disposal time for more complex tasks and when visual rather than auditory cues were presented. Decision hesitations occurred when distractors were present and occurred more when visual compared with auditory stimuli were used. Though decision-response parameters changed, there were no differences in absolute target accuracy or technical hesitation across the complexity levels or stimulus modalities. Skilled athletes are believed to be able to successfully couple decisions with successful execution and the results of this study suggest that increasing task complexity may affect decision-response times, but not the functional skill execution of the handball. The faster response to auditory stimuli and the preference of athletes to attend to this source of information suggest that auditory stimuli should be present and available in decision-making research in the future.

7 Study 6: Cognitive loading and skilled performance: Effects of task difficulty on technique

This study is supported by: Parrington, L., MacMahon, C., & Ball, K. (2014). Read and react: effects of task complexity on motor skill execution. In K. Sato, W.A. Sands, & S. Mizuguchi (Eds.), *Proceedings from the 32nd International Conference on Biomechanics in Sports* (pp. 85-88), Johnson City: East Tennessee State University

7.1 Introduction

In professional sports such as Australian football, athletes are required to perceive and interpret the continually changing game environment and then react in response with technical proficiency. A player with expert technical skill who lacks the ability to choose the best option may be as limited as a player with great decision ability, but poor technical execution. The requirement of balance between both cognitive and motor components is applicable to all sports. Starkes et al. (2004) have suggested a constant interaction between perceptual-cognitive and perceptual-motor skills, and that performance may be constrained (or facilitated) by their interaction.

Little research has been conducted on the interaction between perceptual-cognitive and perceptual-motor ability in complex sport tasks. Bruce et al. (2012) attempted to study the interaction between perceptual-cognitive and perceptual-motor ability and revealed that a lack of motor skill may not influence the decision, but it may limit the ability to successfully execute a given decision. The study by Bruce and colleagues was limited, however, in their ability to provide information on technical adjustments that the players might have made during movement execution, because their analysis of skill was based on pass outcome only. In consequence, they were limited in the capacity to understand any technical underpinnings relating to what component(s) of the motor-skill may by affecting the ability to successfully execute a given decision.

Few researchers have measured kinematic parameters to examine whether a change in motor skill is elicited by changes in environmental complexity or more difficult decision options. Panchuk et al. (2013) assessed whether kinematics and eye movement change dependent on the environmental constraints. Their study found a reduction in skill performance, visual tracking and changes in catching kinematics (e.g. delayed movement initiation, faster hand velocity) when advanced perceptual information was removed. Kannape, Barré, Aminian, and Blanke (2014) looked at the effect of cognitive loading on goal directed behaviour. They found cognitive loading to affect maximum trajectory deviation, walking velocity and motor awareness, but not accuracy or neck yaw. A study by Raab et al. (2005) also analysed kinematic measures on players performing forehand and backhand table tennis shots. The protocol in this study used known and unknown sequence structures to modify the task complexity. Raab and colleagues indicated that changes in transition distance, movement variability and shot accuracy occurred for different testing speeds and complexity (known vs. unknown sequence structure). The focus of Raab et al. was the difference in implicit versus explicit learning. As a result, kinematic measures such as backswing starting position and elbow position were only reported for differences between pre and post learning. Each of these studies demonstrate the use of kinematic data to provide insight into differences in movement or technique that may be occurring as a result of changes to environment or task.

Another area that has received little attention is the use of acoustic information in perceptual-motor responses. Although researchers in the area of motor learning have intended to increase the sensory experience during testing, they have failed to consider this source of information. Responses to visual and auditory sources of information in simple laboratory tasks have been shown to differ. For example, head-eye responses to auditory stimuli are typically faster than responses to visual stimuli (Goossens & Van Opstal, 1997; Sanders, 1998). The results of Study 5 (Chapter 6) demonstrated similar findings when participants were required to handball to the appropriately signalled target with response to auditory targets faster about the body, than responses to visual targets. To extend on these findings it is of interest to know the effects that visual and auditory distractions have on technical performance of the skill (e.g. Langendijk et al., 2001; Öğmen, Ekiz, Huynh, Bedell, & Tripathy, 2013; Röer, Bell, & Buchner, 2014).

Analysing how elite athletes respond technically to performing the same task but with changes in cognitive complexity in a coupled perception-action experimental setting may provide more information on the complex mechanisms underlying skilled performance. Therefore, the aims of this study were to (a) assess whether kinematic differences exist in performing the same motor-skill under different levels of cognitive loading, and (b) to examine whether kinematic differences occur when players respond to auditory versus visual stimuli. This was conducted using a single-subject case study.

7.2 Methods

7.2.1 Participant

The participant was one elite male (23 years, 84 kg, 1.85 m) recruited from a professional Australian Football League (AFL) club. The participant was chosen from the sample of players used in Study 5 based on having the most experience playing at the AFL level (6 years) and the highest accuracy rating of the sample. The participant was undertaking in-season training at the time of testing. Informed consent was required prior to testing and the University Human Research Ethics Committee approved all research methods.

7.2.2 Participant preparation

The participant wore team-training apparel, including shorts, training singlet and running shoes. Prior to testing, he was fitted with movement tracking marker clusters as previously described (Studies 2-4, Chapters 3-5). These marker clusters involved three active markers attached in a non-collinear manner to a rigid heat mouldable plastic that had been form fitted for each body segment. These clusters were attached using a distal under-wrapping technique (Manal et al., 2000). Clusters were attached to the upper and lower extremities (bilateral hand, forearm, upper-arm, shank and thigh) as well as the trunk (pelvis and neck at C7). In order to make the tracking information from these markers meaningful during analysis, anatomical landmarks were virtually stored to allow the definition of anatomical segments and joint centres at the wrist, elbow, shoulder, knee, hip). This is a well-recognised method within biomechanical analysis (Cappozzo et al., 1995).

7.2.3 Equipment

The 360° testing environment replicated the laboratory equipment set up used in Study 5 (Chapter 6). Five bulls-eye targets were equally spaced around the player creating a star formation with one target directly in front and targets equally spaced at the front right and left and back right and left sides. Each target was placed five metres from the central starting position. The centre of the bullseye (0.2 m diameter, 1.5 m high) was fit with an interchangeable blue/ red LED panel. A 6-inch speaker was housed directly below and used to emit auditory stimuli (Figure 7.1).

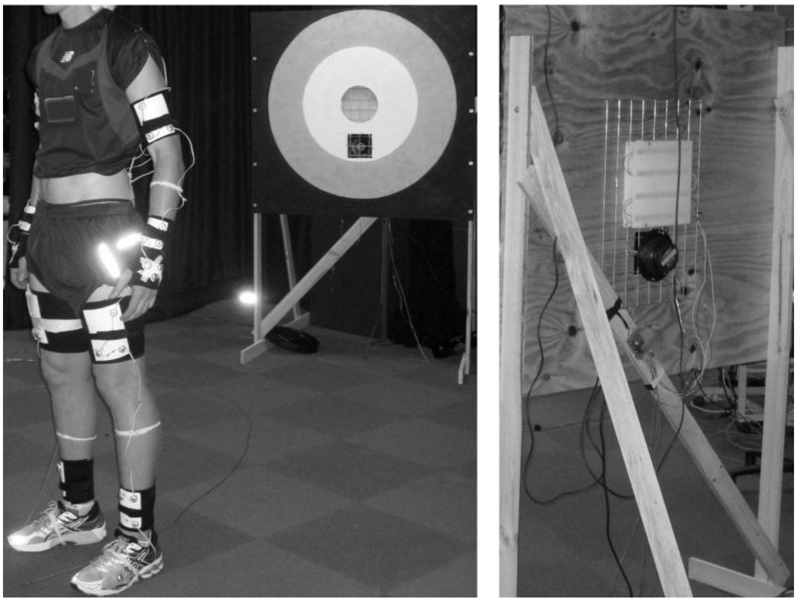


Figure 7.1: Targets used during testing.

All targets were able to emit either visual or auditory signals individually or simultaneously with other target emissions. A player's voice was recorded via a microphone to create the two auditory signals using Mixcraft acoustic software (Acoustica, Inc., Oakhurst, CA, USA). Stimulus emission was controlled via a purpose built interface using LabView (National Instruments Corporation, Austin, TX, USA). The preparation of stimuli settings has been explained in detail in Chapter 6.

7.2.4 Protocol

The participant was fitted with biomechanical tracking markers prior to the onset of the testing protocol. Following this procedure, the participant completed a standardised five-minute warm and ensured the biomechanical marker set-up was not restricting any movement (Chapters 3 – 5). Testing protocol required the participant to complete 34 handballs across four different testing difficulty levels of intended incremental complexity (Table 7.1). The fifth complexity level that is present in Study 5 (Chapter 6) was not included in this study, as results had indicated no differences between level one and level five.

Table 7.1

Breakdown of perceptual-motor task

Complexity level	Trials	Task requirement
1 Simple response (1-SR)	8	One stimulus is emitted from one target only. Handball to target on stimulus signal. Auditory and visual signals tested.
2 Choice response (2-CR)	10	One stimulus is emitted from one of five targets. Handball to the target that emits the stimulus. Auditory and visual signals tested.
3 Choice response with distractor same-modality (3-CRD)	10	Two stimuli are emitted from two of the five targets. One valid and one invalid (distractor). Handball to the target that emits the valid stimulus. Both stimuli are of the same modality (e.g. valid visual signal vs. invalid visual signal)
4 Choice response with distractor different modality (4-CRDX)	6	Two stimuli are emitted from two of the five targets. One valid and one invalid (distractor). Handball to the target that emits the valid stimulus. Stimuli are of differing modalities (e.g. valid auditory signal vs. invalid visual signal)

A two-minute break between each testing level was provided. During this time period, specific task requirements were confirmed with the participant. The participant was instructed to pick up the ball from the ground and perform the handball in the direction of the target that was emitting the valid target stimuli. We requested that the each handball be performed with 'game-intensity' and the player was informed that he was being tested on his handballing accuracy and the time it took to perform the task, although there was no time limit imposed for the response. All testing was completed using an official competition football inflated to 62-76 kPa (Sherrin, Russell Corporation, Victoria, Australia).

7.2.5 Parameter selection

The decision of which biomechanical parameters to include in Study 6 was made through the assessment of Studies 2 – 4 (Chapter 3 – 5). Parameters that were significant in the maximal speed and accuracy based studies (Study 2 and 4) were included in analysis, and any parameters found to differ between the preferred and non-preferred hand (Study 3) were excluded from analysis. Other parameters were removed based on the potential of the task causing differences in parameters that could not be controlled for (e.g. the position of the target would effect trunk rotation).

Seven extra parameters were included outside of these criteria. Shoulder angular velocity was included because it was one of the parameters found to have significant results in each of the studies and it was the parameter that most highly correlated with hand speed (the independent performance parameter) in the maximal handball analysis. Timing data (movement, decision and disposal time) were significant in Study 5 and therefore included in analysis and swing-time was calculated to provide a kinematic temporal measure to aid interpretation of results. Decision and technical hesitations were excluded from analysis in here as only two out of 34 trials (6%) displayed decision hesitations and no technical hesitations occurred for this player. Finally, score and hand speed were included in analysis as a measure of performance. Parameters that were significant in Studies 2-4 are presented in Table 7.2.

Table 7.2

Parameter matrix used for choice of parameters used in Study 6

	Parameter	Maximal (Study 2)	Preferred/ Non-preferred (Study 3)	Accuracy (Study 4)	Affected by target position
Included	Support hand position	X		X	
	Hand path			X	
	Shoulder path	X		X	
	Elbow ROM			X	
	Shoulder ROM	X			
	Elbow angular velocity (max)	X		X	
	Shoulder speed			X	
	Shoulder angular velocity*	X	X	X	
Excluded	Step-angle			X	X
	Separation angle	X			X
	Time to max upper-trunk rotation velocity	X			X
	Shoulder angle	X	X	X	
	Forearm ROM	X	X		
	Lower-trunk ROM		X	X	X
	Upper-trunk ROM		X	X	X
	Forearm angular velocity	X	X		
	Upper arm angular velocity	X	X	X	
	Elbow angular velocity (at BC)	X	X	X	
	Maximum lower-trunk rotation velocity		X	X	X

7.2.6 Biomechanical data collection and analysis

Three-dimensional motion analysis data were collected using the same procedures reported throughout the biomechanical based studies (reported in Chapters 3 – 5), with the following exceptions: (a) the three Optotrak Certus towers were required to be arranged slightly differently about a central calibrated movement area of the player that fit within the centre of the five stimulus presenting targets, (b) the Y-axis of the global reference system was aligned with the frontal target (Appendix F). Processing of raw data was conducted in Visual3D as previously reported (Chapters 3 – 5). Finally, accuracy scores were manually recorded based on a 3-2-1-0 rating (Chapter 6).

7.2.7 Statistical analysis

Statistical analysis was conducted in SPSS 20.0. Parameters (Table 7.3) were assessed using analysis of variance techniques through linear modelling. Cognitive complexity and stimulus modality were analysed separately as fixed factors. Multiple comparisons were assessed for significant differences of complexity level. Effect sizes (Cohen, 1988) were calculated for differences between complexity level and stimulus modality per level.

Table 7.3

Table of parameters

Parameter	Definition
Performance parameters	
Accuracy	Absolute target accuracy based on bulls-eye target (3-2-1-0 scale)
Hand speed	Resultant linear velocity of the hand at ball contact*
Kinematic parameters	
Hand path	Direction of the hand with respect to the line between the hand and the centre of the target at ball contact in the X-Y plane
Shoulder speed	Resultant, linear velocity of the striking arm shoulder at ball contact*
Shoulder path	Direction of the shoulder with respect to the line between the hand and the centre of the target at ball contact in the X-Y plane
Shoulder ROM	Range of shoulder flexion between maximum backswing and ball contact*
Elbow ROM	Range of elbow flexion between maximum backswing and ball contact *
Shoulder angular velocity	The maximum angular velocity associated with shoulder flexion
Elbow angular velocity	The maximum angular velocity associated with elbow flexion
Support hand position	The vertical distance between the support hand and the pelvis
Swing time	Time from maximum backswing to ball contact*
Response-timing parameters	
Decision time	Time from ball possession to ball contact*
Movement time	Time from stimulus onset to ball contact*
Disposal time	Time from onset of stimulus to when the ball has connected with the target

*See Chapter 3 and Appendix F for the determination of maximum backswing and ball contact

7.3 Results

7.3.1 Cognitive loading

Significant differences were found for hand speed and path, shoulder speed, shoulder ROM, shoulder angular velocity and support hand position (Table 7.4). Multiple comparisons between cognitive complexity levels for significant ANOVA findings are presented in Table 7.5.

Table 7.4

Descriptive data and ANOVA result

Parameter		1-SR	2-CR	3-CRD	4-CRDX	ANOVA result
Performance parameters						
Accuracy (score)	M	2	1.8	2	2	$F(3,33) = 0.400$, $p > 0.05$
	SD	0.76	0.42	0.67	0	
Hand speed (m/s)	M	9.11	9.61	8.75	9.2	$F(3,33) = 8.740$, $p < 0.001$**
	SD	0.58	0.42	0.55	0.29	
Kinematic parameters						
Hand path (°)	M	4	9	11	7	$F(3,33) = 5.693$, $p = 0.003$**
	SD	2	6	8	6	
Shoulder path (°)	M	27	18	21	17	$F(3,33) = 1.648$, $p > 0.05$
	SD	16	12	14	10	
Shoulder speed (m/s)	M	1.04	1.31	0.98	1.27	$F(3,33) = 6.160$, $p = 0.003$**
	SD	0.18	0.38	0.47	0.23	
Shoulder ROM (°)	M	45	55	50	55	$F(3,31) = 3.333$, $p = 0.032$*
	SD	4	13	14	20	
Elbow ROM (°)	M	15	13	13	11	$F(3,31) = 2.152$, $p > 0.05$
	SD	3	4	5	4	
Shoulder angular velocity (°/s)	M	640	710	711	713	$F(3,33) = 6.037$, $p = 0.002$**
	SD	25	61	114	80	
Elbow angular velocity (°/s)	M	232	189	208	222	$F(3,30) = 0.882$, $p > 0.05$
	SD	45	65	60	66	
Support hand position (m, %)	M	0.36	0.33	0.31	0.29	$F(3,25) = 6.292$, $p = 0.002$**
		-20%	-18%	-17%	-16%	
	SD	0.04	0.03	0.04	0.05	
		-2%	-2%	-2%	-3%	
Swing time (s)	M	0.12	0.13	0.13	0.13	$F(3,33) = 0.320$, $p > 0.05$
	SD	0.01	0.02	0.03	0.04	
Response timing parameters						
Movement time (s)	M	1.01	1.21	1.29	1.1	$F(3,33) = 6.948$, $p = 0.001$**
	SD	0.07	0.22	0.34	0.31	
Decision time (s)	M	0.46	0.72	0.68	0.78	$F(3,34) = 7.880$, $p < 0.001$**
	SD	0.08	0.22	0.35	0.26	
Disposal time (s)	M	1.54	1.67	1.79	1.59	$F(3,33) = 4.121$, $p = 0.014$*
	SD	0.05	0.22	0.35	0.29	

*Significant difference $p < 0.05$; **Significant difference $p < 0.01$

Table 7.5

Multiple comparisons for significant findings and effect size of the difference

	Level	1-SR			2-CR		3-CRD
		2-CR	3-CRD	4-CRDX	3-CRD	4-CRDX	4-CRDX
Hand speed	Mean diff	-0.5	0.36	-0.1	0.86	0.41	-0.45
	p	0.01*	0.06	0.65	<0.001**	0.04*	0.03*
	d	-0.5	0.315	<0.2	0.879	0.566	-0.532
Hand path	Mean diff	-5	-7	-2	-2	2	5
	p	0.015*	<0.001**	0.272	0.146	0.219	0.016*
	d	-0.548	-0.695	-0.27	<0.2	<0.2	0.326
Shoulder speed	Mean diff	-0.26	0.06	-0.23	0.32	0.03	-0.29
	p	0.01*	0.54	0.04*	<0.001**	0.74	0.01*
	d	-0.471	<0.2	-0.563	0.38	<0.2	-0.415
Shoulder ROM	Mean diff	-10.6	-5.3	-10.53	5.3	0.07	-5.23
	p	0.01*	0.17	0.02*	0.1	0.99	0.15
	d	-0.615	-0.301	-0.436	<0.2	<0.2	<0.2
Shoulder angular velocity	Mean diff	-69.6	-71	-73	-1.4	-3.4	-2
	p	<0.001**	<0.001**	<0.001**	0.94	0.87	0.92
	d	-0.805	-0.511	-0.694	<0.2	<0.2	<0.2
Support hand position	Mean diff	-0.04	-0.06	-0.08	-0.01	-0.03	-0.02
	p	0.01*	<0.001**	<0.001**	0.46	0.1	0.3
	d	-0.497	-0.579	-1.018	-0.308	-0.581	<0.2
Movement time	Mean diff	-0.2	-0.26	-0.08	-0.06	0.11	0.18
	p	0.002**	<0.001**	0.222	0.299	0.089	0.013*
	d	-0.69	-0.683	-0.237	<0.2	0.208	0.292
Decision time	Mean diff	-0.26	-0.22	-0.32	0.03	-0.06	-0.1
	p	<0.001**	0.002**	<0.001**	0.605	0.372	0.184
	d	-0.867	-0.512	-0.941	<0.2	<0.2	<0.2
Disposal time	Mean diff	-0.12	-0.23	-0.05	-0.1	0.08	0.18
	p	0.069	0.002**	0.529	0.118	0.295	0.021*
	d	-0.481	-0.625	<0.2	-0.211	<0.2	0.313

*Significant difference $p < 0.05$; **Significant difference $p < 0.01$

7.3.2 Stimulus modality

When the overall differences between auditory and visual conditions were assessed, disposal time was the only parameter that was significantly different between visual and auditory stimuli ($F(1,33) = 5.649$, $p = 0.023$). Comparisons per level are provided in Table 7.6.

Table 7.6

Descriptive data for performance, kinematic and response timing parameters, and effect sizes for differences in response to auditory and visual stimuli at each complexity level

Parameter		1-SR			2-CR			3-CRD			4-CRDX		
		Auditory	Visual	*d*	Auditory	Visual	*d*	Auditory	Visual	*d*	Auditory	Visual	*d*
Performance parameters													
Accuracy (score)	M	2	2	<0.2	2	2	0.73	2	2	<0.2	2	2	<0.2
	SD	0.8	0.8		0	0.5		0.7	0.7		0	0	
Hand speed (m/s)	M	8.79	9.35	-0.561	9.37	9.85	-0.71	8.96	8.54	0.416	9.16	9.25	<0.2
	SD	0.83	0.17		0.44	0.24		0.32	0.69		0.26	0.38	
Kinematic parameters													
Hand path (°)	M	6	4	0.665	10	8	<0.2	13	10	<0.2	7	6	<0.2
	SD	2	2		7	6		11	5		6	8	
Shoulder path (°)	M	40	17	1.011	16	19	<0.2	14	28	-0.586	17	16	<0.2
	SD	18	4		14	10		10	14		10	12	
Shoulder speed (m/s)	M	1.01	1.07	<0.2	1.22	1.39	-0.218	1.22	0.75	0.58	1.27	1.27	<0.2
	SD	0.28	0.1		0.44	0.34		0.33	0.49		0.26	0.25	
Shoulder ROM (°)	M	47	44	<0.2	57	54	<0.2	47	53	-0.219	58	52	<0.2
	SD	0*	4		18	8		9	18		30	8	
Elbow ROM (°)	M	15	14	<0.2	13	13	<0.2	15	12	0.342	10	13	-0.325
	SD	5	2		2	5		5	5		5	5	
Shoulder angular	M	637	642	<0.2	684	735	-0.459	690	732	<0.2	673	753	-0.632
velocity (°/s)	SD	13	34		73	38		84	145		25	103	
Elbow angular	M	226	237	<0.2	173	203	-0.242	195	218	<0.2	221	223	<0.2
velocity (°/s)	SD	50	48		46	79		60	64		105	57	
Support hand	M	0.4	0.34	-1.303	0.32	0.33	<0.2	0.32	0.3	-0.305	0.23	0.31	1.7
position (m, %)	SD	0.04	0.02		0.03	0.04		0.04	0.04		0*	0.05	
	M	22%	18%		17%	18%		17%	16%		12%	17%	
	SD	2%	1%		1%	2%		2%	2%		-	2%	
Swing time (s)	M	0.12	0.12	-0.288	0.13	0.13	<0.2	0.13	0.13	<0.2	0.14	0.11	0.333
	SD	0.02	0.01		0.02	0.02		0.03	0.03		0.06	0.01	
Response timing parameters													
Movement time (s)	M	1	1.03	-0.302	1.1	1.32	-0.588	1.17	1.44	-0.462	1.07	1.13	<0.2
	SD	0.1	0.02		0.14	0.23		0.1	0.49		0.36	0.33	
Decision time (s)	M	0.42	0.5	-0.676	0.64	0.79	-0.372	0.55	0.82	-0.462	0.75	0.81	<0.2
	SD	0.1	0.02		0.14	0.26		0.11	0.46		0.29	0.27	
Disposal time (s)	M	1.53	1.56	-0.354	1.55	1.78	-0.641	1.64	1.98	-0.582	1.54	1.64	<0.2
	SD	0.07	0.03		0.13	0.23		0.09	0.48		0.35	0.28	

* No SD calculated as only one trial for these conditions due to marker occlusions that could not be interpolated

In the simple response task, the visual condition produced smaller angular displacement for shoulder path and hand path (large and medium effects, respectively), faster linear hand speed (medium effect), a closer support hand to the pelvis (large effect), longer swing time (small effect) and response times (medium effects) in comparison with the auditory condition. In the choice response visual condition, linear hand and shoulder speed, and shoulder and elbow angular velocities were faster (small and medium effects), the accuracy score was lower (medium effect) and response times (decision, movement and disposal) were slower (small and medium effects) compared with the auditory condition. In the same-modality distractor visual condition, shoulder path displayed a larger angle (medium effect), linear hand speed was slower (small effect), elbow ROM was smaller while shoulder ROM was larger (small effects), the support hand was held closer to the pelvis (small effect) and response times were longer (small and medium effects) in comparison with the auditory stimulus condition. In the cross-modality distractor visual condition, elbow ROM was smaller (small effect), shoulder angular velocity was faster (medium effect), the support hand was held further from the pelvis (large effect) and swing time was shorter (small effect). The pattern of shoulder angular velocity and linear hand speed for visual and auditory stimuli per cognitive complexity level are provided in Figure 7.2 and Figure 7.3.

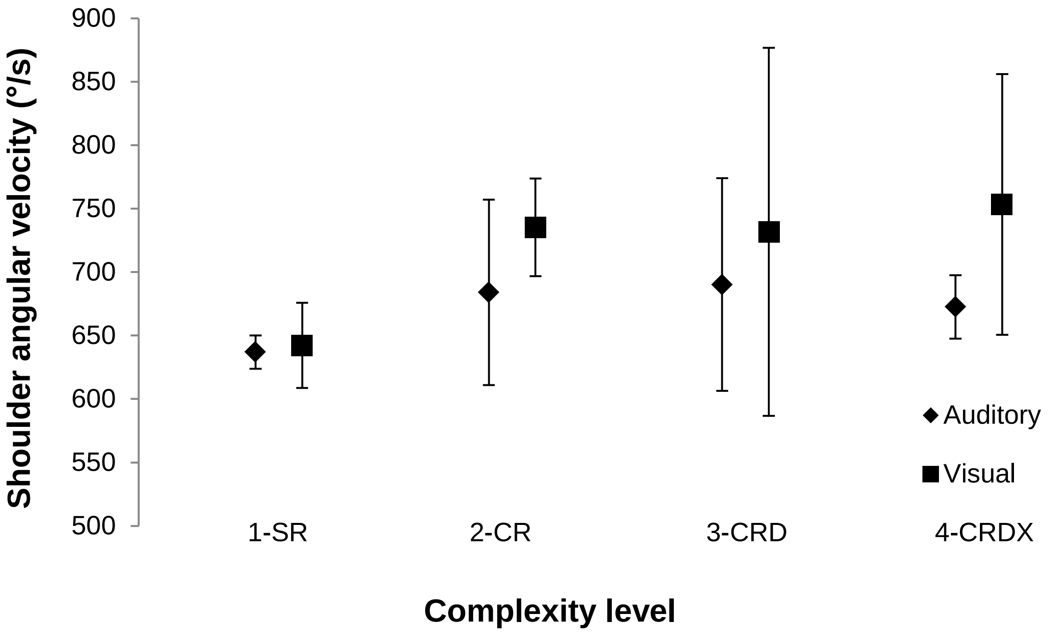


Figure 7.2: Shoulder angular velocity for auditory and visual stimuli per complexity level.

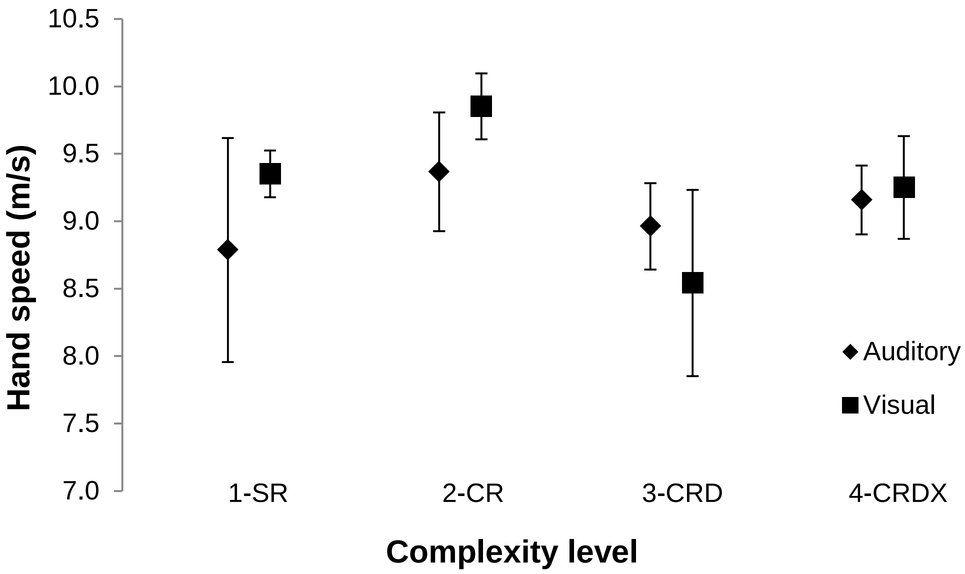


Figure 7.3: Hand speed for auditory and visual stimuli per complexity level.

7.4 Discussion

Handball kinematics and response time parameters were evaluated in this study in order to gain an insight on the interaction between perceptual-cognitive and perceptual-motor skills. This was conducted through the assessment of the effects of cognitive loading and stimulus modality on handballing performance in an elite Australian football player.

Descriptive data for handballing were consistent with previous findings (Chapter 3 – 5), demonstrating that this task was representative of elite handball performance. Hand speed (range 8.54 ± 0.69 to 9.85 ± 0.24 m/s) lay between previously reported values for maximal and accuracy based handballing (e.g. 9.9 ± 0.83 m/s, Chapter 3; 8.23 ± 0.96 m/s to 8.9 ± 1.05 m/s, Chapter 5). This finding was consistent for linear shoulder speed, elbow and shoulder ROM and angular velocities. Two parameters, hand path (range 4° ± 2° to 11° ± 8°) and shoulder path (17° ± 10° to 27° ± 16°), were at a greater angle across the path to the target in comparison with previous results (Hand path: 0° ± 2°, Chapter 5; Shoulder path: 9° ± 10°, Chapter 3; 6° ± 6°, Chapter 5), indicating that at ball contact, the linear path of the hand and shoulder were directed more across, rather than toward the target. This difference may be an outcome of the task requirements of Study 6, where the participant was required to move to handball in a 360° space, while handballs performed in Studies 2 – 4 required the handball to be made forward only.

Cognitive loading and stimulus modality affected skill execution in this participant. Performance was measured by two parameters, hand speed and accuracy. Linear hand speed changed throughout the testing while accuracy was maintained, which is a finding that has been demonstrated in other cognitive loading tasks (Kannape, et al., 2014). The changing velocity but consistent accuracy is plausibly due to the prioritization of accuracy over the speed of the movement (i.e. speed-accuracy trade-off, Fitts, 1954). Each complexity level showed altered technique including different contributions of the parameters analysed. Technical changes are present, however, findings did not show a consistent increase or decrease in the expected direction with cognitive loading changes. Additionally, the finding that swing time did not significantly differ between cognitive conditions, while parameters such as shoulder ROM and hand speed changed indicate that swing time may be an invariant feature of handballing technique (Magill, 2007).

A different technique was used for the simple response task compared with the choice response task. The more complex choice response condition showed faster linear hand and shoulder speed, faster shoulder angular velocity and larger shoulder ROM. As shoulder angular velocity and ROM have been linked to the development of hand speed (Study 2, Chapter 3), these results, in addition to the faster linear speed of the shoulder, suggest that that the player was attempting to move the ball faster (more maximally) toward the target.

The more complex choice response condition also showed the hand path was more angled across the line of the target and the support hand was held closer to the pelvis in comparison with the simple response condition. The more angled hand path found, has been linked with increased hand speed, but decreased accuracy (Parrington et al., 2013; Chapter 5). The mean accuracy score was lower in the more complex choice response task, which may be related to the more angled hand path, however, the difference was not significant. These differences are in agreement with the interpretation of the player attempting to send the ball with greater velocity to the target. The change in support hand position, however, is slightly discordant with these interpretations. In previous studies a closer support hand (vertically to the pelvis) was related to lower hand speed at ball contact (Study 2, Chapter 3) and was a characteristic of the accurate handballing group (Study 4, Chapter 5). In the current study a faster hand speed and less accuracy were indicated in the more complex task. The closer support hand position might have been an attempt to help control the ball for the dual components of speed and accuracy, or aid ball control while responding to the lateral or posterior targets.

Longer movement and decision time in the more complex choice response task was expected due to Hick's Law (Hick, 1952). As swing time did not change, it would indicate that the majority of the time increase was in the preparatory stages of the movement as the participant moved to select which target to handball toward. Disposal time was also longer, based on a small effect for the difference but it was not significant based on $p < 0.05$. The effect that the longer movement and decision response had on disposal time (time from stimulus onset to ball contact with the target) may have been slightly countered by the faster hand speed. A faster hand speed would have likely resulted in greater ball speed and decreased flight time of the ball. In other words, an increased hand speed may have been an attempt by the player to speed up the overall performance.

The presence of same-modality distractors affected technique. In this condition the participant was instructed to attend only to the valid stimuli and ignore the invalid stimuli provided as a distraction. This condition was subject to both Hick's Law, as well as the influence of distractors. The choice response task provides a useful comparison, as it is subject to Hick's Law but not distractors. In comparison with the choice response task, linear hand and shoulder speed were slower in the presence of same-modality distractors, suggesting that the presence of distractors make up a component of the difference. Distractors (invalid cues) are believed to divert or shift attention from the valid stimuli and have been implicated with longer response times, slower breaking initiation times and a more intense physical response in driving research (Hancock et al., 1999; Hancock et al., 2003; Janelle et al., 1999). Results indicate that the increase in disposal time is an outcome of later initiation of the downswing movement, because swing time (time between maximal backswing and ball contact) was consistent throughout complexity levels. As the linear speeds measured were slower in this condition, there was no indication of a more intense physical response in the same modality distractor condition.

The cross-modality distractor also affected technical performance, with differences revealed between this task and the preceding cognitive loading levels. In comparison with the simple response task, faster shoulder speed and shoulder angular velocity, larger shoulder ROM, a support hand position vertically closer to the pelvis and longer decision time were noted. Interestingly here, the faster shoulder speed and shoulder angular velocity did not result in a faster hand speed. Comparatively, performance on the cross-modality distractor task appeared to be closer to the choice response task. Slower hand speed and a closer support hand position in the cross modality distractor condition were the only differences (based on significance or medium effects) between these two levels. Differences between same-modality and cross-modality distraction tasks were noted, including faster linear speeds, more direct hand path and shorter movement and disposal time in the cross-modality condition. Interestingly there was no significant difference, nor effect, in decision time, although mean values indicate that this parameter was longer in the cross-modality task. The differences between the cross-modality distractor in comparison with the same-modality distractor for this participant indicate a better performance for the cross-modality task.

The effects that auditory and visual stimuli have on response times appear clearer than the effects on movement kinematics. Response times were faster to auditory compared with visual stimuli, fitting with previous findings that head-eye responses are typically faster to auditory stimuli than responses to visual stimuli. However, kinematic data do not provide the same clarity. Based on hand speed, performance changed with the complexity level and differed the least in the cross-modality distractor condition. Mean shoulder angular velocity was less in response to auditory stimuli, though small and medium effects were only seen in the choice response and the cross-modality distractor condition. The positive relationship between hand speed and shoulder angular velocity (Study 2, Chapter 3) would suggest that hand speed should therefore be slower in response to auditory stimuli, which is indicated for the simple response and choice response tasks (medium effects) and represented by the mean values in the cross-modality distractor condition. However, in the same-modality distractor condition, hand speed was faster for the auditory response. Shoulder speed followed a similar pattern, with slower speed (or no difference) for all levels bar the same-modality distractor condition. The differences noted for elbow and shoulder ROM in the distractor conditions appear to indicate a difference in contribution or coordination of the joints, with greater elbow ROM but less shoulder ROM presented for response to auditory stimuli and vice-versa for visual stimuli. Though the kinematic data do not indicate that one form of modality presents distinctly better kinematics than the other, differences are indicated. Therefore, anyone wishing to replicate a team sport environment, where players are required to react to a stimulus during testing conditions should take both visual and auditory information into account in order to get a better representation of game-like conditions.

Results for both complexity level and stimulus modality indicate differences between the responses to distractors of the same-modality versus different modality. Findings such as a faster hand speed and more direct hand path as well as quicker movement and disposal times indicate better performance on the cross-modality task. Under complex movement, the effect of distractors within the same-modality may be more problematic than cross modal distractions. This might be explained by the under the selective transfer framework. Öğmen et al., (2013) suggested that if visual information is first scrutinised to determine validity, with only valid information transferred to visual short term memory then distractors would slow the process of transfer from sensory memory to visual short term memory. In the cross-modality condition, this suggested 'bottleneck' may not occur because there is only one valid visual component to transfer. From an auditory perspective, a more pronounced distraction occurs when the stimulus sequence violates expectations developed during prior exposure to regular auditory sequences (Röer et al., 2014). As the participant was first accustomed to the valid stimulus cue in the simple response task and choice response task, the concurrent auditory signal used to distract may have caused more of a shock in same modality distraction condition. Contrastingly, during the cross modality distraction condition the unpredictable nature of the invalid distractor cue may have worn off, causing less of a distraction effect. Additionally, the presence of acoustic distractors affects the ability to localise target sound (Langendijk et al., 2001), but may not influence the participant's ability to recognize a visual cue.

This study indicates that the nature and complexity of the task may affect research findings. This is an important consideration for biomechanical analysis of any sports skill as it poses the question of whether data collected from a controlled laboratory setting is applicable to skills that typically take place within a complex environmental setting. This study indicates that the handball technique was representative of handballs made in the more controlled tasks (Study 2-4, Chapters 3-5), but also highlights the fact that technical differences occurred with differences in the cognitive task condition. Measuring skills in a controlled environment eliminates the effects of external influences, which can help researchers to focus on particular components and features of performance. In contrast, measuring in a complex environment introduces the potential for external influences to have an effect on the technical performance of the skill. These effects may aid in the discovery of new parameters or parameters that vary dependent on task requirements. Therefore, researchers should consider these factors in addition to the research question prior to designing and implementing biomechanical study designs.

The results of this study highlight the benefits of a multidisciplinary approach where biomechanical information is collected. Many authors in motor learning research use only an outcome-based parameter. Had this approach been taken in this study, the conclusion would have been that performance as indicated by accuracy did not change. However, there were substantial changes in how the technique was produced. While this does not alter the validity of previous findings, it does identify that a greater understanding of the motor-skill may be gained through kinematic analyses.

The differences found in this study indicate that future research is warranted. The use of a dynamical systems approach to gain a greater understanding of how technique and coordination profiles are effected under cognitive loading provides an interesting avenue for further research. Analysis should be should be conducted on a larger sample of elite Australian footballers in order to address whether these findings are more widely generalisable. Assessment using a group-based approach might be appropriate, however, multiple individual-based studies or the combination of both methods may provide a more thorough investigation of the effects of cognitive loading and stimulus modality on motor-skill execution (Ball & Best, 2007).

7.5 Conclusion

This case study was used to explore whether kinematic differences existed in motor-skill execution under different levels of cognitive loading of the task, and whether there were any differences in responding to auditory versus visual stimuli. For this participant, cognitive loading and stimulus modality affected skill execution. The effects of cognitive load on performance were indicated by hand speed differences, but not accuracy. Technical differences between cognitive complexity levels occurred for hand path, linear shoulder-speed, shoulder ROM, shoulder angular velocity, support hand position and response time parameters. While each complexity level showed altered technique, findings did not indicate a consistent increase or decrease in the expected direction. Overall, total disposal time was the only parameter found significantly different between auditory and visual stimulus conditions. However, when the visual and auditory conditions were assessed per level using effect sizes, differences emerged. Response times were the most consistent, being faster to auditory stimuli in the first three cognitive complexity levels. Smaller elbow ROM and larger shoulder ROM occurred for visual in comparison with auditory stimuli in the same-modality condition, while larger elbow ROM and smaller shoulder ROM occurred in the cross-modality condition.

Findings have implications for both biomechanical and motor learning research. Data indicate that the environmental complexity of the task may affect motor-skill execution and therefore research findings. Kinematic analyses conducted during this study were able to provide more detailed technical information that could not be provided by the outcome parameter ‘score’. That kinematic differences were found, while changes to outcome score were not, provides further evidence for the usefulness of a multidisciplinary approach, which combines motor learning and biomechanics.

8 General Discussion

8.1 Summary

Research throughout this thesis used a multidisciplinary approach to analyse a specific motor skill (handballing in Australian football) in order to observe the technical and cognitive mechanisms underlying skilled performance. The study sought to answer three questions; what defines successful handball performance during games? What defines successful handball performance technically? And, what happens to handballing performance under changes to cognitive load? The three disciplines used to answer these questions were performance analysis (Study 1), biomechanics (Study 2, 3 and 4) and motor learning (Study 5 & 6).

Handballing performance was first assessed in Study 1 using a skill-focussed performance analysis of games from the AFL. The purpose of this analysis was to create a profile of in-game handball executions by identifying and separating the physical (technical), cognitive (decision-making) and game/ environmental factors. In addition, the manner in which these factors influenced successful in-game performance of the handball was assessed. Identification of these physical and cognitive components was then used to guide the subsequent biomechanical and motor-learning studies (Study 2 through to Study 6).

The biomechanical analyses were divided into three categories to assess the movement parameters that lead to better technical performance, including (a) kinematic factors related to handballing maximally for speed using the preferred hand, (b) kinematic differences between handballing with the preferred and non-preferred arm, and (c) accuracy and speed-accuracy considerations. Speed, accuracy and bilateral ability are necessary components of handballing passing skills and thus, essential components for inclusion in research on this skill (Parrington, Ball, MacMahon, & Taylor, 2009; Parrington et al., 2012; Parrington et al., 2013a).

Studies 5 and 6 used a novel stimulus-response paradigm to assess perceptual-motor skill and technical performance together. Both studies examined the skill execution of the handball under changes to cognitive task complexity and stimulus modality (auditory/ visual). Study 5 was developed to assess response time parameters, hesitations and outcome, while Study 6 focussed on kinematic differences. Previously, researchers have focussed on cognitive factors when a combined perceptual-cognitive/ motor performance methodology has been used (e.g. Bruce et al., 2012; Mann et al., 2010; Müller & Abernethy, 2006; Müller et al., 2009). Conversely, Study 5 and 6 focussed on the changes that occur with the motor performance of the skill. Parameters assessed in Study 6 were driven by the performance and biomechanical analyses (Chapters 3 – 6).

This chapter is divided into two sections. The first includes a discussion of the issues that are common across the multiple studies in this thesis, including the strengths and weaknesses of the approaches used. In the previous sections, Studies 1 to 5 of this thesis have been presented in their published or current manuscript review format. That particular format had not thoroughly allowed adequate discussion of some issues for the purposes of this thesis. The second section of this discussion thus expands on issues specific to particular chapters, in order to provide a complete evaluation of the issue at hand, including potential limitations.

8.2 General discussion of common issues

8.2.1 Multiple disciplines: multiple perspectives

This thesis uses both independent and collaborative contributions from three research disciplines in an attempt to understand the mechanisms underlying skilled performance. The research methods, which are characteristic of different disciplines, are able to provide particular components of information that are complimentary to each other. When undertaking research from the perspective of one discipline in isolation, researchers may overlook some key characteristics of performance. In contrast, by considering multiple research disciplines within this thesis (performance analysis, biomechanics, motor learning) a more holistic knowledge base about the skill was developed. This multidisciplinary approach provided an extensive evaluation of handballing in Australian football and the effects of cognitive task changes on technical performance.

Performance analysis (Chapter 2) was able to provide game-specific information, which has the potential to drive further analysis (discussed further in Section 8.3.1). Using this approach provided a description of the skill and the conditions or environment in which it is performed. For example, performance analysis was able to identify that 64% of handballs were performed when the player was square to their intended passing target and that when squared, 91% of passes were successful (Parrington et al., 2013b [Chapter 2 of this thesis]). These types of data provide an evidence base to identify the factors that are important to successful handballing during games. This demonstrates the strength of the performance analysis discipline.

Although performance analysis is a useful tool, the application is limited in ability to assess the underlying mechanisms that influence performance. In contrast, biomechanical analysis can assess these technical attributes and provide a more precise description of the movement. Therefore, the next step in the thesis was to use the process of biomechanical analysis in combination with performance analysis to gain a greater understanding of the mechanisms involved in handballing in Australian football. This combined approach is beneficial because three-dimensional biomechanical analyses are typically difficult (if not impossible) to perform during live game settings due to the complications related to measurement during such scenarios (i.e. camera positioning, cumbersome equipment).

The three biomechanical studies (Chapters 3 – 5) provide further evidence of the benefit of assessing a skill from multiple perspectives. Each of these studies had a different kinematic focus (maximal handball for speed or distance, preferred and non-preferred hand differences, handball for accuracy and combined speed-accuracy). Certain parameters were identified as statistically significant in more than one study (e.g. shoulder angle at ball contact). The identification of these influential parameters is practically significant, as these parameters contribute to handballing regardless of the goal of the skill. In contrast, there were three parameters present in Study 4 (Chapter 5) that were not statistically significant in the prior two studies. This finding demonstrates that certain parameters were particular to the task (e.g. hand path, step-angle and elbow ROM for accuracy).

Study 5 and 6 used a complex motor task to assess performance differences in response to increased choices, distractions and type of cue. Together, these two studies combined to form a multidisciplinary approach. Study 5 (Chapter 6) observed differences from a motor-learning perspective, assessing accuracy, response times and hesitations across five levels of complexity. Using the same novel task, Study 6 (Chapter 7) included significant parameters from Studies 2 – 5 and provides a clear demonstration of the connection between each of the disciplines.

Parameters identified as statistically significant in biomechanical Studies 2-4 are identified in Table 8.1.

Table 8.1

Parameters found to have significant relationships or differences in biomechanical studies

Parameter	Maximal (Study 2)	Preferred vs. Non-preferred (Study 3)	Accuracy Speed-accuracy (Study 4)
Support hand position	X		X
Hand path			X
Shoulder path	X		X
Elbow ROM			X
Shoulder ROM	X		
Elbow angular velocity (max)	X		X
Shoulder speed			X
Shoulder angular velocity	X	X	X
Step-angle			X
Separation angle	X		
Time to max upper-trunk rotation velocity	X		
Shoulder angle	X	X	X
Forearm ROM	X	X	
Lower-trunk ROM		X	X
Upper-trunk ROM		X	X
Forearm angular velocity	X	X	
Upper arm angular velocity	X	X	X
Elbow angular velocity (at BC)	X	X	X
Maximum lower-trunk rotation velocity		X	X

8.2.2 The use of multiple sources of background information to drive selection of parameters

In previous research, some authors have failed to explain why certain parameters were chosen for analysis (e.g. Dichiera et al., 2006), while other authors have based their decision on only one source of information (e.g. previous findings, Sachlikidis & Salter, 2007). In comparison, this thesis used four sources of input to guide the choice of parameters. First, previous literature was eliminated as a viable source of information upon consideration that Australian football literature has addressed kicking, but no literature on handballing was available to guide parameter selection. Thus, the four sources of input included (a) a deterministic model (Appendix A), (b) coaching cues from coaching literature, (c) coach feedback on what was considered important, and finally, (d) the in-game performance analysis (Parrington et al., 2013b [Chapter 2 of this thesis]). The use of multiple sources of input to drive the selection of key parameters for investigation considers both theoretical and evidence-based approaches and, therefore, provided a strong rationale for the parameters chosen throughout this thesis.

Deterministic models are paradigms based on Newtonian physics used to help determine the relationship between independent movement parameters and dependent outcome parameters (Chow & Knudson, 2011). Chow and Knudson recommend the use of deterministic models to assist the provision of a theoretical basis for sport biomechanics research. Conversely, other researchers have indicated that deterministic models are restricted with respect to the information provided concerning 'technique' (Glazier & Robins, 2012; Glazier & Wheat, 2013). In this thesis, the deterministic model was used to gain an initial understanding and aid in the derivation of underpinning mechanical factors of the Australian football handball. The process provided a useful tool, which aided the process of parameter selection, but was not the sole source of input.

The second source of input used in this thesis included deriving parameters from coaching literature. This method involved assessment of the key qualitative coaching instructions and translation of these instructions into measurable parameters (Table 8.2).

Table 8.2

Coaching instruction and parameter derived

	Instruction (McLeod & Jaques, 2006)	Parameter
1	Grip ball with stationary support hand	Support hand position / support hand position from pelvis
2	Punch ball from support hand using clenched fist	Hand velocity
3	Step forward to gain power and distance	Step length, knee angle, linear velocity (trunk/ shoulder/ hip)
4	Follow through with punching hand in a motion upward and toward the target	Hand path

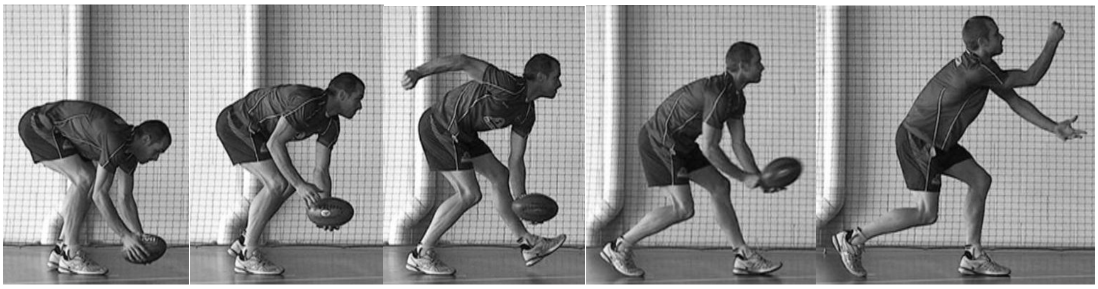
In addition to the use of coaching literature, coaching information was also obtained through consultation with coaching staff from one of the AFL clubs. Here, the coaches were asked what facets of handballing performance were important. In particular they were asked to describe using coaching terms the type of movement the ‘good handballers’ possessed. The coaches described terms such as ‘being square’, ‘good backswing’, ‘striking through, not across the ball’, and ‘taking a step forward and knees bent’ as features of good handballing. Some of these parameters had obvious and direct links with terms used in the deterministic model (e.g. the hand path at ball contact with ‘striking through and not across the ball’) while some were more specific to what could be observed but not directly related (e.g. ‘being square’ might be connected with the position of the upper and lower trunk with respect to the passing target). Terms that were closely linked were associated with parameters in the deterministic model, while others were translated into new technical parameters (Table 8.3).

Table 8.3

Coaching cue and parameter derived

	Coaching cue	Parameter
1	Being square	Upper and lower trunk orientation Separation angle Upper and lower trunk range of motion Trunk / shoulder / hip path toward target
2	Good backswing	Shoulder range of motion Elbow range of motion
3	Striking through, not across the ball	Hand path Lateral deviation of the striking hand
4	Taking a step forward and knees bent	Step length Step direction Knee angle (flexion)

Qualitative observations from video footage of two players selected as the top handballers at the club were used to support the coaches' descriptions (Figure 8.1). This method provided a useful applied approach toward research of a motor-skill. In addition, conducting analysis of parameters based upon coaching cues allows evaluation of these cues and helps to provide evidence for or against their use in practice.



2 hand contact	Onset of backswing	Maximum backswing/ onset of downswing	Ball contact	Follow through

Figure 8.1: Handball performed by a player described as one of two top handballers at the club at the time of testing.

The skill-focussed performance analysis used in Study 1 (Chapter 2), was the final source of parameter input. The identification of critical features relating to live match performance is believed to be good common practice (Hughes & Bartlett, 2002) and has been suggested to compliment biomechanical and decision-making evaluation (Ball & Horgan, 2013; Glazier, 2010). It is beneficial to use as a precursor to further analysis because of the ability to categorise predominant skill executions and separate physical and cognitive components of the motor-skill to retrieve a greater insight into performance (Ball & Horgan, 2013). Knowing the common skill executions is useful to direct further testing, such that the testing conditions can reflect the typical skill performance (Ball & Horgan). The implementation of findings from the performance analysis is provided in Table 8.4.

Table 8.4

Implementation of parameters from skill-focussed performance analysis

	Parameter	Finding	Implementation
1	Being square	More commonly performed when square Higher efficiency when square	Assess whether upper and lower trunk orientation with respect to target increases accuracy (Parrington et al., 2012).
2	Player stance/ motion	Stationary passes occur more often than in motion Running and 'knees-bent' stance more efficient	Influenced starting position for biomechanical testing. Players started from a stationary position and were able to take a step (or shuffle) forward. Kinematic assessment of knee-angle and linear speed of the hip and shoulder.
3	Pass direction	Forward passes most common and most efficient	Biomechanical testing focussed on forward passes. Assess hand path (Parrington et al., 2012).
4	Pass distance	Short passes (6m or less) more common	Biomechanical assessment of passes performed at similar distance.
5	Number of options	One to two passing options in clear support of ball carrier	Studies 5 and 6 used one valid option and one invalid option. Study 5 included one level of two but competing valid options.
6	Time to dispose ball	Between one and three seconds most common but time to dispose did not influence efficiency	Player instructed to perform under game intensity, but not constrained by time.

Finally, the decision of which biomechanical parameters to include in Study 6 was made through the assessment of Studies 2 – 4. Parameters that were significant in the maximal speed and accuracy based studies (Study 2 and 4) were included in the analysis, and any parameters found to differ between the preferred and non-preferred hand (Study 3) were excluded from analysis. Other parameters were removed based on the potential of the task causing differences in parameters that could not be controlled for (e.g. the position of the target would effect trunk rotation).

Using multiple sources of input, including theoretical models and evidence-based coaching information and game analysis, was a robust approach to select parameters. It is important to consider multiple sources of input as each source might introduce a new parameter, or may provide additional support for the collection of a particular parameter.

8.2.3 Issues related to cut-off frequency and filtering biomechanical data

The identification of cut-off frequency for filtering biomechanical data is a prevalent issue in biomechanics research. Because of a region of signal and noise overlap, there is a need to find the best compromise between noise reduction and signal elimination (Winter, 2009). A fourth-order low-pass Butterworth filter was used in this thesis. The decision to use a fourth-order Butterworth filter over other methods (e.g. Fourier Series, Hatze, 1981; Jackson, 1979; Spline smoothing, Woltring, 1985) was based on its widespread use within biomechanics (Ball, 2008; Ball, 2011b; Ball, Best, & Wrigley, 2001; Ball, Best, & Wrigley, 2003a; Ball, Best, & Wrigley, 2003b; Dörge, Bull-Andersen, Sørensen, & Simonsen 2002; Nunome, Ikegami, Kozakai, Apriantono, & Sano, 2006; Panchuk et al., 2013; Werner et al., 2006).

There are a number of methods, which have been used in the determination of optimal cut-off frequency for Butterworth filters. These methods include the use of: visual inspection (Ball, 2008; Ball, 2011b; Ball & Best, 2007); previously published values (Ball, 2011b); automated methods (Yu, 1989; Yu et al., 1999; Winter, 2009; Challis, 1999); spectral analysis (Ball et al., 2001) and inspecting the influence of different cut-offs on parameters of interest (Ball & Best, 2007; Ball, 2008). The limitations of these methods include the lack of objectivity (visual inspection), not accounting for variations in analysis protocols and data quality (previously published values), over-smoothing at high frequencies (residual analysis), and not accounting for variation in the quality of raw data sets collected at the same sampling frequency (estimations based on sampling frequency). Additionally, Giakas & Baltzopoulos

(1997b) suggested that estimation for optimal cut-off frequency should not be purely based on displacement data.

Giakas and Baltzopoulos (1997a) and Ball et al. (2001) provide evidence that there is no optimal solution for the selection of cut-off frequency to filter biomechanical data. Giakas and Baltzopoulos (1997a) advise researchers to take the assumptions and limitations of the method(s) employed into account. Ball et al. (2001) suggested that both objective (automated methods) and subjective (visual inspection of curves) should be considered when deciding on a smoothing cut-off. Based on the recommendations of these authors, the determination of the cut-off frequency used to filter biomechanical data in this thesis was based on a combination of residual analysis (objective), visual inspection of resulting curves (subjective), and spectral analysis to assess system noise and the effect on parameters of interest using a range of cut-offs in support. A description of the process is provided in Appendix B (Winter, 2009).

Residual analysis was selected as one methodology because of its common application within sport biomechanics research (drop-punt kicking, Ball, 2008; golf, Ball & Best, 2007; shooting, Ball et al., 2003a; Ball et al., 2003b; soccer kicking, Dörge et al., 2002; catching, Panchuk et al., 2013) and because of the ability to gain data specific cut-off information. The main limitation of this method is that is has been suggested to over-smooth data (Giakas & Baltzopoulos, 1997a; Yu et al., 1999). Giakas and Baltzopoulos (1997a) found that residual analysis tended to under estimate the cut-off frequency of displacement data in comparison with the five other methods assessed (e.g. power spectrum analysis, regularised Fourier series); however, residual analysis did not perform as poorly for first or second derivative data.

Yu et al. (1999), also demonstrated that the cut-off value determined through residual analysis was below the optimum cut-off, especially for higher frequencies (Figure 8.2).

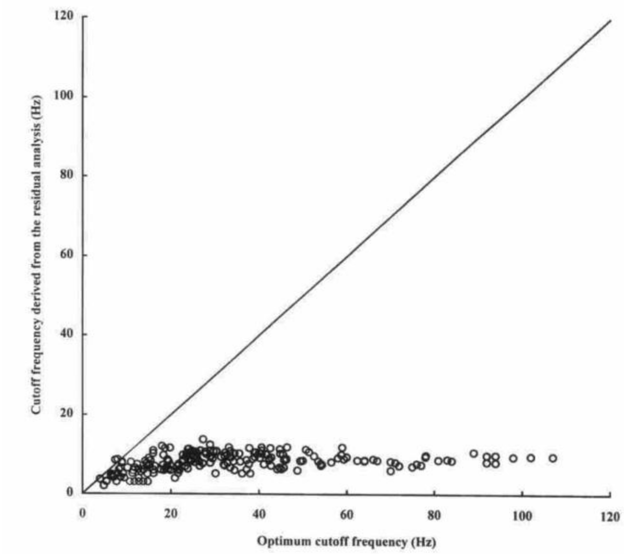


Figure 8.2: Figure replicated from Yu et al. (pg. 327, 1999) – The relationship between the optimum cut-off frequency derived from residual analysis.

A comparison of four methods used on three different datasets, however, demonstrated that other methods also indicate low values (Ball et al., 2001). Although Yu and colleagues (1999) indicate that residual analysis may over smooth and that their method more closely reflects the optimal cut-off frequency, in some data sets, the cut-off determined by Yu et al. (1999) was lower than other methods (Table 8.5).

Table 8.5

Table replicated from Ball, Best and Wrigley (pg. 1, 2001) – The optimal cut-off frequency determined by four methods tested

	Golf Swing				Shooting		Walking	
	Front foot		Back foot					
	CPx	CPy	CPx	CPy	CPx	CPy	x	y
Challis (1999)	11.0	17.5	11.5	34.5	9.5	32.5	12.5	12.5
Yu et al. (1999)	24.7	24.6	25.3	24.7	7.5	9.7	3.0	3.5
Winter (1990)	14.0	15.0	14.0	14.0	6.0	5.5	10.0	4.0
Jackson (1979)	-	-	-	-	6.0	8.0	4.0	8.0

To substantiate the use of residual analysis, findings were compared against the method proposed by Yu et al. (1999). For a 100 Hz sample rate, the optimal cut-off according to Yu's automated selection equation is 9 Hz (Yu, 1989). The full protocol for the estimation of optimum cut off frequency requires calculation and use of the relative mean residual. Using this process, the calculation indicated that data should be filtered at 6 Hz, which was lower than the 7 Hz average selected through residual analysis.

Although objective determination of the optimal cut-off frequency is warranted, given the discrepancies of the varying methods, using one method alone in preference to another method has been suggested to add subjectivity (Ball et al., 2001) and therefore evaluation of a number of methods (residual analysis, visual inspection, spectral analysis and comparison of effects on parameters of interest) provides a strong basis for the choice of cut-off in this thesis.

The evaluation of how cut-off frequency affects different outcome measures is one consideration, which is rarely addressed in the literature (c.f. Ball et al., 2001; Ball, 2008). As Yu et al. (1999) suggested that the optimal cut-off frequency determined through residual analysis (7 Hz) would over smooth the data; it was compared with the optimal cut-off determined by Yu's automated calculation (9 Hz, Yu, 1989). Firstly a comparison of the squared residuals at 7 and 9 Hz was completed. The difference between these two cut-off frequencies ranged between 1.0×10^{-5} and 2.0×10^{-6}, suggesting little meaningful difference between the two cut-off frequencies. Secondly, two of the key parameters that were identified as having the strongest correlation in Study 2 were reassessed using a 9 Hz cut-off.

This was performed using a random subset of half of the participants in order to assess the difference between the values produced using 7 Hz versus 9 Hz as the filter cut-off frequency (Table 8.6).

Table 8.6

Difference in two key parameters (Hand speed and shoulder angular velocity) when filtered at 7 and 9 Hz

Participant	Hand speed (m/s)		Shoulder Angular Velocity (°/s)	
	7 Hz	9 Hz	7 Hz	9 Hz
1	10.4	10.6	221	222
2	8.2	8.3	90	91
3	9.2	9.4	212	211
4	9.7	9.9	148	150
5	10.2	10.3	612	619
6	8.6	8.9	176	176
7	10.4	10.5	352	354
8	10.3	10.5	225	224
9	9.4	9.6	204	206
Average	9.6	9.8	249	250

The average differences in hand speed and shoulder angular velocity were 0.2 m/s and 1 °/s, respectively. In addition, the difference in the correlation coefficient between these two parameters for 7 Hz and 9 Hz was 0.0129 and did not change the effect size (r = 0.55 for 7 Hz, r = 0.54 for 9 Hz) of the correlation coefficient between these two parameters. Furthermore, the same conclusions would have been reached had either cut-off been used. This finding demonstrates, though there is a need to choose an appropriate cut-off frequency, that there is a tolerance level to which it may not functionally affect the data.

In summary, the use of 7 Hz as the cut-off frequency for filtering the biomechanical data was built upon the advice of Ball et al. (2001) and Giakas and Baltzopoulos (1997a). Four methods were used in the determination of this cut-off frequency (see Appendix B). Comparing the effect of cut-off frequency on parameters of interest is less commonly used, but was a useful step in this thesis to help validate the selection of the cut-off frequency.

8.2.4 Task fidelity and the use of visual and auditory stimuli

The novel motor task design used in Studies 5 and 6 (Chapter 6 & 7) is a strong feature of this thesis. It represents the first to measure changes in response performance to increasing task complexity using both visual and auditory stimuli in a complex motor skill. The findings of these studies pose the question of whether auditory cues should be included in addition to visual stimuli in future motor learning research (e.g. anticipation, perception and decision making) to increase task fidelity.

Increased task fidelity is believed to better extract or “tap in” to features of expert performance. Visual information has been at the core of many task designs in motor learning, including those implementing high fidelity settings (e.g. Bruce et al., 2012; Mann et al., 2010; Müller & Abernethy, 2006; Müller et al., 2009). The data presented within Study 5 highlights the potential importance of including auditory stimuli in future studies. Williams and Ericsson (2005) indicated that a task should be representative of the real performance domain in order for true characteristics of elite performance to be elicited. The findings of Study 5 are noteworthy because they suggest different responses for auditory and visual cues, both of which are present in a game environment. This is evidenced by the differences in response times to auditory stimuli in comparison with visual stimuli and the higher frequency of responses to auditory stimuli when players were given the choice to handball to either cue.

In sporting environments, especially for team sports, both auditory and visual cues are available in the form of valid and invalid stimuli. Players may both scan visually and listen out for verbally presented signals from teammates. Conceptually therefore, it is evident that both auditory and visual information should be included in research designs that are wishing to advance testing fidelity.

In addition to how these findings may impact motor learning research, the results from Study 6 (Chapter 7) have implications for biomechanical evaluation studies. As differences in kinematics were shown to occur for different complexity tasks, these findings present a question to biomechanical theorists on the environment and testing conditions employed in different studies. If environmental task complexity affects the kinematics of performance, then knowing what setting best represents the game environment and conditions of performance would be preferable during testing. In principle, an understanding of this can be gained through performance analysis, which reinforces the benefits of a multidisciplinary approach to skill assessment.

8.3 Expanding on issues specific to chapters

8.3.1 Performance analysis: advantages and limitations

Both advantages and limitations exist in relation to the skill-focussed performance analysis used in this thesis. Performance analysis was beneficial because it allowed a profile of handball use in games to be developed, which included execution, environment and outcome factors. The profile of handball was then used to help guide the testing procedures. Specifically, execution factors including the length (0-6 m), direction (forward), pre-execution motion (stationary) were chosen for biomechanical assessment as these were the most prevalent features of in-game handball execution (Parrington et al., 2013b [Chapter 2 of this thesis]). Although performance analysis was used to guide research methods in this thesis, this type of process also has high potential to be used to assist coaching staff in the planning of training sessions.

Secondly, the skill-focussed performance analysis was advantageous because of the ability to derive additional contextual information of what factors influenced the success of the pass. This methodological approach was solid because the interaction of skill and successful play is believed to be an important contribution to the successful outcome of games (Bartlett, 2001). Publically available statistics only include basic counts of skill executions and outcomes. For example, the National Rugby League (NRL) provides information about the number of tries, tackles and run metres (NRL statistics, 2014), while for AFL, statistics provided include number of disposals, overall disposal efficiency, marks and tackles (Australian Football League, 2013b). In comparison, more detailed statistics providers employed by clubs produce a greater range of statistics than these websites such as a stratification of kicking and handballing efficiency (Champion Data, 2012). Nevertheless, there are still limited statistics provided on technical, decision making and environmental factors that may influence the overall performance of a player, especially in relation to a specific skill such as handballing.

Performance analysis conducted in this thesis was able to provide additional contextual information on performance, such as which factors related to the occurrence of effective and ineffective passes. This is of particular benefit, from both a research and applied coaching perspective, because it allows critical factors to be highlighted, confirmed or challenged. For example, in consultation with coaching staff, players ‘squaring up’ when handballing was discussed as an important factor underlying handballing success. The findings from Study 1 indicate that efficiency was 21% higher when players were square to their target when passing. Furthermore, the results provide evidence that help to validate ‘squaring up’ as a factor of handballing performance. As a result of this finding, the motion and position of the lower and upper trunk were assessed technically in the kinematic analysis.

Thirdly, contextual information from performance analysis is beneficial because it provides the ability to look at how different aspects of performance interrelate. That is, skill-focussed performance analysis allows one or more factors to be analysed in combinations to observe any influence and help aid the interpretation of data. For example, data from Parrington et al. (2013b [Chapter 2 of this thesis]) demonstrated that passes made from a non-squared stance occurred under greater levels of high and moderate pressure, which can assist interpretation of why these passes were less efficient, as increased pressure negatively influenced efficiency. Moreover, this level of detailed information allows coaches and researchers to measure a specific parameter against other factors (e.g. pressure) in order to understand more about game events.

Finally, performance analysis is advantageous because of the ability to be conducted without the use of expensive equipment. The evaluation of in-game handball use was conducted on readily available game footage from the 2008 and 2009 AFL seasons. This is an advantage to anyone wishing to conduct this style of analysis, as most teams, regardless of skill level, have access to a video camera and basic computer software.

A limitation of this method was the time required for the data collection. Due to the data being manually recorded and the high number of skill executions per game, skill-focussed performance analysis was very time consuming. At least two to three replays of each handball was often required in order to tease out each of the parameters collected in the analysis conducted in Study 1 (Chapter 2).

Performance analysis is a valid and reliable technique, but it is not able to collect the same scale of technical information as biomechanical analysis. For example, due to continuously changing camera perspectives used in live footage, actual distance of handballs could not be measured using performance analysis. As a result, handball distance was categorised in a binary and qualitative fashion, as either short or long, rather than a quantitative value. Although acknowledged here as a possible limitation, it was not considered an issue in this thesis.

In addition, performance analysis is unable to provide information on underlying mechanisms and processes that underpin the outcome (Glazier, 2010). Understanding this limitation, this thesis used the skill-focussed analysis to identify the profile of skill executions in addition to linking parameters to handball performance (% Efficiency). The analysis was aimed at assessing the influence of technical, decision-making and pre-execution factors (leading up to the handball), rather than determining the underlying mechanisms. Thus, despite the limitations identified, the utility of this methodology outweighed the potential drawbacks.

8.3.2 The use of canonical correlation

A strong feature of this thesis was the use of canonical correlation analysis (CCA), which was conducted in Study 4 (Chapter 5) as a method of analysing performance requiring accuracy and speed. In ball sports, the speed of ball travel and accuracy of delivery are important in many skills (Table 8.7).

Table 8.7

Examples of sport skills where both speed and accuracy are important

Sport	Skill	Speed	Accuracy
Baseball	Fast pitch	Increase difficulty of bat-ball interception	Pitch required within strike zone
Cricket	Fast-bowling	Increase difficulty of bat-ball interception	Bowler aims to hit wickets
Rugby (Union or League)	Conversion kick	Achieve distance of goal	To place ball in between goal posts
AFL	Set shot for goal	Achieve distance of goal in air to avoid interception of defender	To place ball between central goal posts for 6 points
Tennis	Serve	Increase difficulty for the opponent to return ball	Ball is often delivered as low as possible for speed and as close as possible to the edge of the service square
Volleyball	Serve	Increase difficulty for the opponent(s) to intercept	Ball aimed toward point of weakness in opposition
Association football (soccer)	Penalty kick	Increase difficulty of goaltender saving ball	Ball placed to a particular position in the net

This thesis demonstrates the use of CCA to assess this relationship. The method can be used to assess other multivariate relationships where a skill performance requires achieving more than one dependent variable.

There are a number of strengths to the use of CCA. The first of these is that it is able to provide information on relationships both between and within both independent (covariate) and dependent (criterion) variables, without the need to conduct separate analyses (i.e. analysis for speed and analysis for accuracy). Secondly, there is no need to divide the sample, or run multiple statistical tests between groups, which can inflate type 1 error (Sherry & Henson, 2005). Another benefit is that the relationships provided by the canonical correlations and structure coefficients can be interpreted like *R* in regression analysis and effect sizes can be readily interpreted using Cohen's *r* (1988) interpretations.

Analysing speed and accuracy concurrently can identify factors that are important to both but might not be identified when these components are examined in isolation. In this thesis, elbow ROM was an important contributor to the canonical model for both hand speed and accuracy, but was not significantly related to either factor when measured separately (Parrington et al., 2013a; Chapter 5). So had CCA not been performed, this component would not have been identified as potentially important.

There are some limitations that exist with CCA. The most predominant limitation is the lack of understanding throughout the research community on how to perform and/ or interpret these types of analyses (Sherry & Henson, 2005; Tabachnick & Fidell, 2007). Though it has been used previously in the area of biomechanics (e.g. Babić, Harasin, & Dizdar, 2007; Leigh, Gross, Li, & Yu, 2008), a lack of literature relating to the use of CCA is perhaps one reason for its limited use in comparison with other statistical methods (Pearson's correlations, regression, multiple regression) in spite of the advantages of its use.

Due to of the complex nature of the analysis, both between and within covariate and criterion groups, interpretation of CCA can be more difficult than the interpretation of more conventional methods. Furthermore, interpretation of the CCA output requires three main steps:

1. Assessment of the full canonical model to determine the whole relationship. The full canonical model evaluates the shared variance (e.g. relationship between the group of movement parameters and group of performance parameters). Here, the researcher should assess both the statistical significance (*p*-value) and the effect (r^2), which can be interpreted like R^2 is in multiple regression (Sherry & Henson, 2005). The r_c value can also be calculated from r_c^2 and interpreted like correlation coefficients using Cohen's *r* (1988) effect sizes.
2. Assessment of the canonical functions to determine which should be interpreted further. Again, the significance and effect size should be used in the decision making process. Tabachnick and Fidell (2007) suggested the cut-off for continuing analysis is $r_c > 0.3$ ($r_c^2 > 10\%$).
3. Interpretation of the structure coefficients of each canonical function (where warranted, based on step 2). The structure coefficients provide information on the contribution and direction of the relationships of parameters within the function (Sherry & Henson, 2005).

Another limitation to the use of CCA is the lack of strict guidelines for case to independent variable ratio. The ratio has been indicated as at the authors' discretion, with a suggested case-to-independent variable ratio of 5:1, with lower ratio acceptable when data reliability is high (Tabachnick & Fidell, 2007). As is the case with other statistical processes, a larger number of participants may avoid results being too specific to the sample used and more generalisable to the population.

A practical limitation exists in current statistical practices where code/syntax is required to be written rather than using pre-defined menu options and ‘wizard’ windows. This might deter some researchers who prefer to use statistical packages with more easily functioning menu options (e.g. SPSS). Nonetheless, there are example scripts for different statistical packages (e.g. SPSS, SAS) available where all that is required is for the dependent and independent variables to be entered into the syntax in the appropriate area.

The use of canonical correlation analysis in Study 4 highlights the benefits of this statistical process for biomechanics researchers wishing to analyse the contributions to optimal performance where more than one performance parameter are required for success. Researchers in other areas of sport science may also find these methods beneficial to use in order to simultaneously analyse multivariate relationships between multiple independent kinematic parameters and dependent variables.

9 Overall conclusion

The performance of skills within team sport is multifaceted in nature, requiring a complex combination of technical and cognitive expertise. Although analysing one discipline will provide important information, the assessment of a motor-skill across multiple disciplines, as conducted in this thesis, has demonstrated a deeper and more comprehensive understanding of the skill. The foundation of this thesis has been built upon three research disciplines in order to assess performance of a specific skill (the “handball”) within a team sport (Australian football): performance analysis, biomechanics and motor learning. Application of this combined approach has great potential for the analysis of any motor skill pertaining to the field of sport and exercise science.

The first aim of this thesis was to profile the Australian football handball as it is used in elite competition and assess how technical, decision-making and game-environment or lead-up conditions relate to a successful outcome in the Australian Football League. This aim was achieved using a novel, purpose-built performance analysis system, which allowed the evaluation of handball executions based on theoretical and coaching information.

The technical profile of the handball within Australian football most commonly included a squared and stationary stance, with short passes being made to the front, not across the body. The decision-making profile included players most commonly under low pressure, with one or two passing options available, and made passes within one and three seconds of receiving the ball. The most common game-environment conditions included handballs made in the midfield, and when the lead up prior to the handball included the football being caught in the air and after the ball had been travelling direct toward the player.

The profiling of the most common handball executions in Australian Football League games guided evaluation in the subsequent biomechanical and motor learning studies in the following way: (a) evaluation involved forward aimed handballs only, (b) the target distance was set according to the short passing distance, (c) players were asked to perform handballs at game intensity (without induction of other pressure), and (d) presentations of one or two simultaneous stimuli were presented during trials of the motor learning perceptual-motor task.

Performance analysis also provided information regarding how each parameter affected outcome, the efficiency of the handball. Technically, positioning the body square to the target (trunk facing the target), passing the ball in a forward direction, passing while running or using a stance involving bent knees were all evident in efficient handballs. Of the decision-making factors, higher efficiency occurred when there was less pressure and more options in support of the ball carrier. Game-environment factors demonstrated handballs were more efficient in the defensive 50 and when the ball had easily been received through a catch in the air and with the ball moving toward the player.

Efficiency data were also used to guide biomechanical evaluation. Technical factors related to efficiency were used to derive a number of kinematic parameters that were assessed, including (a) upper and lower trunk range of motion, position at ball contact and rotational velocities (squared stance), (b) knee angle (knees-bent stance), (c) linear speed of the hip and shoulder (running stance), and (c) path of the hand (forward passes).

The second aim of this thesis was to identify kinematics important for handballing in maximal and accuracy conditions, as well as differences for preferred and non-preferred hand. The assessment of technical factors associated with handballing maximally for greater speed was conducted in Study 2.

Study 2 provided descriptive data for handballing for maximal speed and identified three technical parameters that relate to the development of hand speed for contact with the football. The study indicated that maximising the speed of shoulder flexion during the swing phase should be a point of focus for coaches who wish to increase a players' maximal handball speed or distance. Increasing shoulder joint range of motion by increasing the backswing may help facilitate the production of shoulder angular velocity. The correlation between shoulder angular velocity and forearm and upper-arm speed suggest informing players to "swing the arm through faster" may be potentially useful as a cue to increase hand speed. Results also demonstrated that some hand speed may be accounted for by trunk motion. Timing of maximal trunk rotation was important and linked to faster hand speeds when it occurred just prior to ball contact (95% movement time). As separation angle at ball contact was also related to hand speed, rotating the upper-trunk in order to face the target for ball contact has good potential as a coaching cue to increase hand speed.

Technical differences between preferred and non-preferred limbs were analysed in Study 3. A more developed movement pattern was evident in the preferred-arm, making greater use of the trunk, shoulder and arm, resulting in greater hand speed. The preferred arm exhibited greater linear speeds (maximum lower-trunk speed and strike-side hip-speed), greater angular velocities of the lower- and upper-trunk, forearm, upper-arm and shoulder, but a lesser elbow angular velocity in comparison with the non-preferred arm. Body position at ball contact was also different, with shoulder angle, lower- and upper-trunk orientation angle smaller in the preferred-arm at ball contact, while support elbow angle, ROM in trunk (lower and upper), forearm, upper arm and range of lateral trunk flexion were smaller in the non-preferred arm.

Accuracy and speed-accuracy considerations were assessed in Study 4. When accuracy was assessed by dividing subjects into accurate and inaccurate groups, the accurate group exhibited less elbow ROM and angular velocity and a more direct path of the hand towards the target, in comparison with the inaccurate group. When assessed *within-subject* assessments were performed for successful versus unsuccessful handballs, less elbow ROM was also noted in successful handballs. Successful handballs were also characterised by greater trunk motion (upper- and lower-trunk ROM and lower-trunk rotation velocity) and step-angle in comparison with the unsuccessful handballs. When *within-subject* analyses were performed for accurate and inaccurate groups, shoulder linear velocity, lower- and upper-trunk ROM and lower-trunk rotation velocity were greater in the successful in comparison with the unsuccessful handballs within the inaccurate group. Finally, canonical correlation analysis identified a strong relationship between accuracy and hand speed and the following movement parameters, (a) elbow ROM, (b) elbow angular velocity, and (c) hand path. Interpretation of this canonical model indicated that reducing elbow joint motion might assist the stabilisation of the arm movement for a controlled fist contact with the ball and greater accuracy; however, this may reduce possible ball contact speed.

The final aim of this thesis was to identify whether perceptual-motor performance changed as an outcome of cognitive complexity or stimulus modality. This aim was achieved through the combination of Studies 5 and 6. Study 5 demonstrated differences in handball performance occurring under different levels of cognitive complexity and stimulus conditions. Slower movement, decision and disposal times were evident in more complex conditions and under visual in comparison with auditory stimuli, however, handball accuracy was unaffected. Decision hesitations occurred during cognitive complexity increases, which involved distractions. Study 5 also found that players handballed more frequently to auditory in contrast to visual stimuli when they had the option to attend to whichever they preferred.

Finally, Study 6 demonstrated that technical differences were evident for responses to changing levels of cognitive complexity and different stimulus modalities. Although the kinematic differences existed, the changes did not seem to follow a pattern in one specific direction as the task complexity changed. Indicated differences in the movement pattern, however, suggest that caution should be applied when determining testing or training environments as the kinematics of the player might change dependent on the task. Additionally, the benefits of a multidisciplinary approach were highlighted as the outcome parameter ‘accuracy score’ was unable to indicate significant differences, but kinematic parameters were statistically significant.

Skilled performance within team sports requires multiple layers of expertise, which drives the need to derive information about performance from more than one perspective. A theoretical groundwork about how this may be achieved through the assessment of multiple disciplines, both in isolation and in combination with each other, has been presented in this thesis. The application of such a multidisciplinary approach has provided a thoroughly considered understanding of the one skill (handballing in Australian football). This motor skill has acted as a platform to highlight the benefits which accompany a combined approach. Future multidisciplinary collaborations may have an impact on the quality of information derived from research on skilled performance, ultimately providing more information to players, coaches and fellow investigators.

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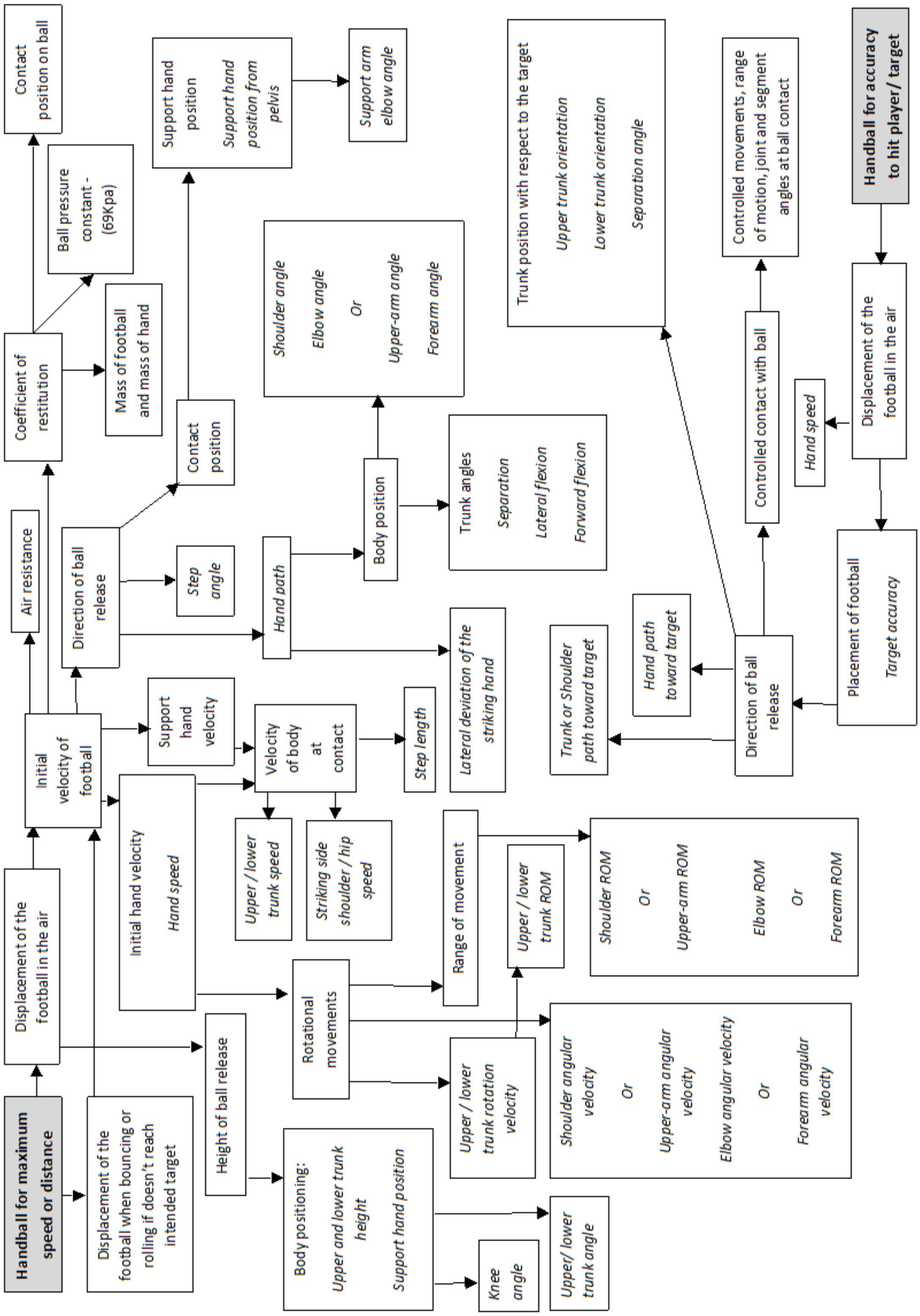
Appendix A

Deterministic model for handballing



Appendix B

Filtering of Biomechanical data and determination of cut-off frequency

Digital filtering was conducted in Visual3D in order to remove any noise from the signal. A low-pass filter was used because of the need to keep the lower frequency signal and attenuate any higher frequency noise. Unfortunately there is a region of signal and noise overlap, which means the cut-off frequency (f_c) needs to balance noise reduction and signal elimination. Because of this compromise, Winter (2009) indicates that signal distortion and noise passed through the filter should be equal.

The f_c used in biomechanical assessment in throughout this thesis was determined through a combination of residual analysis and visual inspection of velocity-time curves. Cut-off frequency was also crosschecked against automated methods suggested by Yu et al. (1999). Residual analysis was determined as the best method to determine f_c because it observes the residual error over a wide range of cut-off frequencies and includes the characteristics of the filter in the transition region.

Residual analysis was performed on a randomly selected 5 participants to examine the effect of different cut-off frequencies on each segment (lower and upper trunk, bilateral thigh and shank, bilateral upper arm, forearm and hands). Using methods outlined by Winter (2009), each segment was smoothed at f_c ranging from 5 Hz to 15 Hz using a fourth order Butterworth digital filter. The residuals for each trajectory were calculated and the residual error was plotted against f_c (Figure B.1).

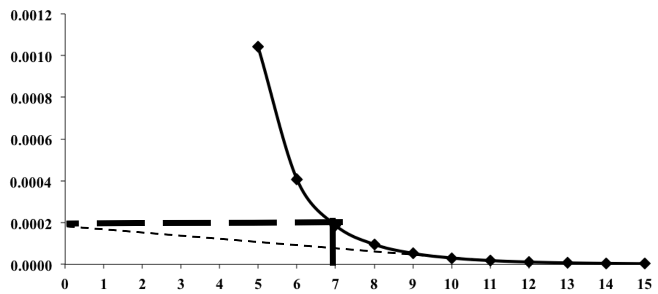


Figure B.1: Example of residual errors plotted against cut-off frequencies for 5 – 15 Hz.

This process was conducted for x, y and z coordinates for each participant and was then plotted in a table. The average f_c was determined for each segment across the five participants (Table B.1). This average was then selected as the cut-off frequency.

Table B.1

Cut-off frequencies (Hz) determined through residual analysis per subject for x, y and z coordinates

	X VALUES					
	SUB01	SUB02	SUB03	SUB04	SUB05	AVERAGE
Left upper arm	8	7	7	6.5	7.5	7
Left forearm	7	7.5	7.5	7	7	7
Left hand	X	7.5	7	6.5	7	7
Left shank	7.5	6.5	7.5	6.5	7	7
Left thigh	7.5	6.5	7	6.5	7.5	7
Right upper arm	7	7	6.5	6.5	7.5	7
Right forearm	6.5	7	6.5	6.5	7	7
Right hand	7	6.5	7	6.5	6.5	7
Right shank	7.5	7	6.5	6.5	7	7
Right thigh	7.5	7	6.5	6.5	7	7
Lower trunk	7.5	7	7	7	7	7
Upper trunk	7	X	7	6.5	7	7
	Y VALUES					
	SUB01	SUB02	SUB03	SUB04	SUB05	AVERAGE
Left upper arm	8	7	7	6.5	7.5	7
Left forearm	8	7	7	6.5	7.5	7
Left hand	X	7	7.5	6.5	7.5	7
Left shank	8	6.5	7	6.5	7.5	7
Left thigh	7.5	6.5	7	6.5	7	7
Right upper arm	7.5	7	6.5	6.5	7	7
Right forearm	7.5	7	7	6.5	7.5	7
Right hand	7	6.5	7	6.5	7	7
Right shank	7.5	7	6.5	7	7	7
Right thigh	8	7	6.5	6.5	7	7
Lower trunk	7	7	7	7	6.5	7
Upper trunk	7	X	7	6.5	7	7
	Z VALUES					
	SUB01	SUB02	SUB03	SUB04	SUB05	AVERAGE
Left upper arm	7.5	7	7.5	6.5	7.5	7
Left forearm	7.5	7.5	7	6.5	7.5	7
Left hand	X	7	7	6.5	7.5	7
Left shank	8	6.5	7.5	6.5	7	7
Left thigh	7.5	6.5	7	6.5	7	7
Right upper arm	8	7	6.5	6.5	7	7
Right forearm	8	6.5	7	6.5	7.5	7
Right hand	7	6.5	7	7	7	7
Right shank	7.5	7	7	6.5	7.5	7
Right thigh	7.5	7.5	6.5	6.5	7	7
Lower trunk	7.5	7	7	6.5	7	7
Upper trunk	7	X	7.5	6.5	7.5	7

The conclusion from the residual analysis was that data should be filtered using a f_c of 7 Hz. After the data were filtered, visual inspection of both trajectory and velocity curves was conducted in order to confirm that this smoothing cut-off was appropriate (Figure B.2).

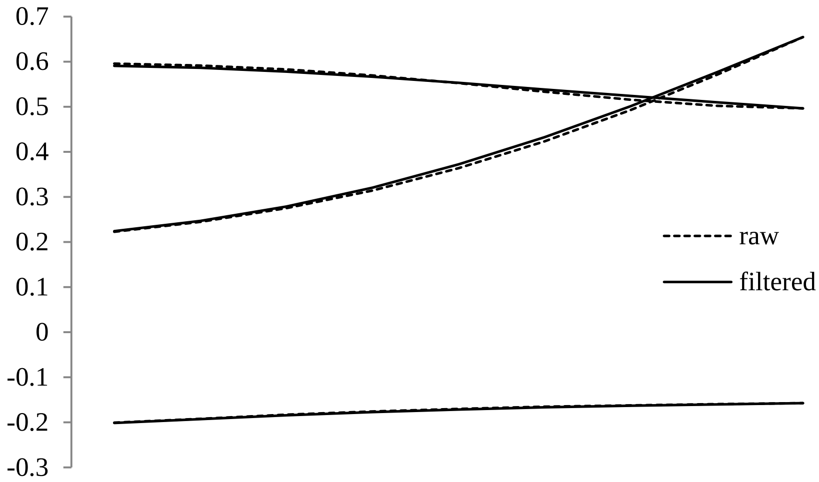


Figure B.2: Example of raw data signal and filtered data signal for hand position (x, y and z coordinates).

Appendix C

Ethics approval

VICTORIA UNIVERSITY | A NEW SCHOOL OF THOUGHT

MEMO

TO	Dr Clare MacMahon School of Exercise & Sport Science Footscray Park Campus	DATE	15/04/2011
FROM	Dr Anthony Watt Chair Arts, Education & Human Development Human Research Ethics Subcommittee		
SUBJECT	Ethics Application – HRETH 09/10		

Dear Dr MacMahon

Thank you for resubmitting this application for ethical approval of the project:

HRETH09/10 A multidisciplinary analysis of handballing in Australian Rules football: A biomechanical and decision making analysis

The proposed amendment and extension requests have been accepted and deemed to meet the requirements of the National Health and Medical Research Council (NHMRC) 'National Statement on Ethical Conduct in Human Research (2007)', by the Chair, Faculty of Arts, Education & Human Development Human Research Ethics Committee. Approval has been granted from 15/04/2011 to 30/06/2011.

Continued approval of this research project by the Victoria University Human Research Ethics Committee (VUHREC) is conditional upon the provision of a report within 12 months of the above approval date (by **15/04/2012**) or upon the completion of the project (if earlier). A report proforma may be downloaded from the VUHREC web site at: http://research.vu.edu.au/hrec.php

Please note that the Human Research Ethics Committee must be informed of the following: any changes to the approved research protocol, project timelines, any serious events or adverse and/or unforeseen events that may affect continued ethical acceptability of the project. In these unlikely events, researchers must immediately cease all data collection until the Committee has approved the changes. Researchers are also reminded of the need to notify the approving HREC of changes to personnel in research projects via a request for a minor amendment.

If you have any further queries please do not hesitate to contact me on 9919 4119.

On behalf of the Committee, I wish you all the best for the conduct of the project.

Kind regards,

Dr Anthony Watt
Chair
Faculty of Arts, Education & Human Development Human Research Ethics Subcommittee

Appendix D

Information to participants

INFORMATION TO PARTICIPANTS INVOLVED IN RESEARCH

You are invited to participate

You are invited to participate in a research project entitled “A multidisciplinary analysis of handballing in Australian Rules football”.

This project is being conducted by a student researcher Ms. Lucy Parrington as part of a PhD study at Victoria University under the supervision of Dr. Clare MacMahon and Dr. Kevin Ball from the School of Human Movement, Recreation and Performance.

Project explanation

The purpose of this research is to assess the technical and decision making components of handballing in Australian football. This will be evaluated using two testing sessions. The first testing session will look at technique during handballing. The second testing session will look at decision making, eye-movement and technique during handballing. Each testing session will take approximately one hour to complete. During this time you will be briefed on each of the activities, fitted with specialised equipment, given time to warm up to this equipment and then asked to perform a series of handballs.

What will I be asked to do?

1. Come to two testing sessions (approximately one hour each)
2. Wear your basic football training gear (football shorts and jersey or similar)
3. Have specialised markers attached to your
    a. legs (calf area and thigh area)
    b. arms (bicep area, wrist area and hand), and
    c. torso (neck and back/ hip area)
4. Wear an eye-movement registration system during the second testing session
5. Perform a standard handball with both your left and right hands –
    a. Handball for maximum distance (testing session 1)
    b. Handball aiming at a target (testing session 1)
    c. Handball to one of seven targets positioned to your front, side and back
6. Perform a basic movement pattern (e.g. taking a three step run up or moving at a moderate pace from side to side) prior to making each handball.

What will I gain from participating?

Participation in this study is voluntary; however, there are potential benefits if you choose to partake in this research. If requested, you will be provided with a record of your own personal results which you may use to identify areas for improvement in your handball technique and decision making ability. Additionally, by participating in this study you are assisting in the development of evidence-based technical cues that can be used for coaching at all levels. Furthermore, you will be helping to provide information on decision making under different modes of sensory detection. This will also provide you with information on how you respond to visual and auditory stimuli (what you see vs. what you hear).

How will the information I give be used?

The results will be used to provide and develop information to assist the coaching of handballing in Australian Rules football. The results will be used to help coaches and players understand how to best perform the skill of handballing. This will help new players learn how to handball, and will assist current players in developing or refining their technique.

Additionally, you will be helping to provide information on decision making under different modes of sensory detection (e.g. vision vs. sound), and under different levels of task complexity.

What are the potential risks of participating in this project?

The participants of this study will be required to perform a basic movement pattern (e.g. taking a three step run up or moving at a moderate pace from side to side) prior to making each handball. This movement pattern will not involve any unexpected changes or deviations in movement. The physical risk included in this movement pattern as well as making the handball will not pose any risk to the participant greater than what would occur during practice conditions.

How will this project be conducted?

Participants will be required for two testing sessions which will approximately take one hour each to complete. During both testing sessions participants will be fitted with special markers, used to record three-dimensional coordinates of body movement. These markers will be placed on the upper extremity (upper arm, forearm and hand), lower extremity (lower leg and thigh) and torso (upper and lower back/hip area). Markers are fitted using specialised elastic material, sports tape, and sports adhesive spray and will not hurt during attachment and removal. Markers may feel slightly awkward to start with but participants will be given time to get comfortable before any testing takes place. This marker system is commonly used in sports biomechanical analyses around the world.

During the first testing session participants will be asked to make five maximal distance, and five short-accuracy passes with both their right and left hands (20 handballs in total).

In the second testing session, participants will be fitted additionally with a head mounted eye-movement registration system. This system is used to pick up information on where the participant is looking during the handball. Wearing this equipment is similar to wearing a pair of big glasses. The attachment or removal of this system will not hurt in any way, but the participant may feel strange at first. The system will be fitted securely on the participants head just before performing the handballs.

During the second testing session participants will be asked to handball to one of seven potential targets positioned to your front, side and back. For each trial, a flash, sound, or combination of both will indicate which target to hit. The aim will be to pass as quickly and as accurately to the appropriate target.

The participants of this study will be required to perform a basic movement pattern (e.g. taking a three step run up or moving at a moderate pace from side to side) prior to making each handball. This movement pattern will not involve any unexpected changes or deviations in movement.

Who is conducting the study?

This study will be conducted through Victoria University.

Researchers		
Dr. Clare MacMahon School of Human Movement, Recreation and Performance Victoria University Footscray Park Campus Ballarat Road, Footscray 3011 Tel: (03) 9919 5410 Clare.MacMahon@vu.edu.au	Dr. Kevin Ball School of Human Movement, Recreation and Performance Victoria University City Flinders Campus 301 Flinders Lane, Melbourne 3000 Tel: (03) 9919 1119 Kevin.ball@vu.edu.au	Ms. Lucy Parrington PhD Candidate School of Human Movement, Recreation and Performance Victoria University Footscray Park Campus Ballarat Road, Footscray 3011? Tel: (08) 83021524 0407 151 825 lucy.parrington@live.vu.edu.au

Any queries about your participation in this project may be directed to the Principal Researcher listed above.
If you have any queries or complaints about the way you have been treated, you may contact the Secretary, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4781.

Consent forms

CONSENT FORM FOR PARTICIPANTS INVOLVED IN RESEARCH

Researcher's name Ms. Lucy Parrington
Supervisor's name(s) Dr. Clare MacMahon
Dr. Kevin Ball

Research title: A multidisciplinary analysis of handballing in Australian Rules football.

INFORMATION TO PARTICIPANTS:
We would like to invite you to be a part of a study into the technical and decision making performance of handballing in Australian Rules football. This project is currently being conducted at Victoria University by Ms. Lucy Parrington, Dr. Clare MacMahon and Dr. Kevin Ball.

The purpose of this research is to assess the technical and decision making components of handballing in Australian football. The primary aims for this research are:

- To explore both technical and decision making factors pertaining to handballing
- To compare the importance of visual and auditory stimuli in the handball technique

You will be asked to:

1. Come to two testing sessions (approximately one hour each)
2. Wear your basic football training gear (football shorts and jersey or similar)
3. Have specialised markers attached to your
    a. legs (calf area and thigh area)
    b. arms (bicep area, wrist area and hand), and
    c. torso (neck and back/ hip area)
4. Wear an eye-movement registration system during the second testing session
5. Perform a standard handball with both your left and right hands –
    a. Handball for maximum distance (testing session 1)
    b. Handball aiming at a target (testing session 1)
    c. Handball to one of seven targets positioned to your front, side and back
6. Perform a basic movement pattern (e.g. taking a three step run up or moving at a moderate pace from side to side) prior to making each handball.

Anonymous group-based information will be provided back to your coaches. You may obtain a copy of your own data and can hand this to your coach or give us permission to give your data to your coaches in the interest of improving your performance.

Participation in this study is voluntary. If at any stage during the testing you do not wish to continue, you may stop the testing and discontinue participation without penalty or prejudice.

If at any stage you become anxious or distressed you may take a break or withdraw from the study. Dr Mark Andersen, a registered psychologist at Victoria University, independent of this study, is available if you wish to discuss any issues regarding your participation.

By participating in this research you will:

1. Be provided with a record of your own personal results which you may use to identify areas for improvement in your handball technique and decision making ability, including how you respond to visual and auditory stimuli.
2. Assist in the development of evidence-based technical cues that can be used for coaching at all levels.
3. Help provide information on decision making under different modes of sensory detection.

CERTIFICATION BY SUBJECT
I, ... (Full name)
of .... (Suburb)
Certify that I am at least 18 years old and that I am voluntarily giving my consent to participate in the study: A multidisciplinary analysis of handballing in Australian Rules football being conducted at Victoria University by: Ms. Lucy Parrington, Dr. Clare MacMahon and Dr. Kevin Ball.
I certify that the objectives of the study, together with any risks and safeguards associated with the procedures listed hereunder to be carried out in the research, have been fully explained to me by: .... (Name of researcher)
and that I freely consent to participation involving the below mentioned procedures:

- I understand that I may not directly benefit from taking part in the project.
- I understand that I can withdraw from the study at any stage and that this will not affect my status now or in the future.
- I understand that all electronic data will be stored on the researcher's personal computer under secure password protection until the completion of the research.
- I understand that an electronic back-up of the data will be stored on the researcher's personal external hard-drive and that this information is stored under secure password protection until the completion of the research.
- I understand that all hard copy data will be stored in a locked cabinet in the Biomechanics Laboratory at Victoria University and that only the student researcher (Ms. Lucy Parrington) and the research supervisors (Dr. Clare MacMahon and Dr. Kevin Ball) will have access for the purposes of analysis. This data will be held for a period of five (5) years and then destroyed.
- I grant the University the exclusive and royalty free right to reproduce and use in its ongoing activities photographs, video, or any other recording by any means of my voice or physical likeness which is produced in the course of the project.
- I understand that the University shall not be required to make any payment to me arising out of its exercise of this right.
- I understand that wherever practical, the University will acknowledge my participation in the project in exercising this right.
- I have read the Participant Information Sheet, and the nature and the purpose of the research project has been explained to me. I understand and agree to take part.

□ I wish for my data to remain anonymous and to only be presented to my coaches as de-identified group data

□ I wish for a copy of my data, which I may provide to my coaches if I wish to do so. I understand that my data will be presented to my coaches as de-identified group data.

□ I give permission to the researcher to provide a copy of my personal data to my coaches. I understand that my data will be presented to my coaches as de-identified group data also.

I certify that I have had the opportunity to have any questions answered and that I understand that I can withdraw from this study at any time and that this withdrawal will not jeopardise me in any way.
I have been informed that the information I provide will be kept confidential, unless I have otherwise given permission for my results to be provided to my coaching staff only, by ticking the appropriate box above.

Name of participant: ....
Signed: ....
Dated: ....

I have explained the study to subject and consider that he/she understands what is involved.
Researcher's signature and date

....

Any queries about your participation in this project may be directed to the researcher
Ms. Lucy Parrington
School of Human Movement, Recreation and Performance
Victoria University
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Mob: 0407 151 825
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If you have any queries or complaints about the way you have been treated, you may contact the Secretary, Victoria University Human Research Ethics Committee, Victoria University, PO Box 14428, Melbourne, VIC, 8001 phone (03) 9919 4781

Appendix E

Western Bulldogs Football Club Letter of Support

Western Bulldogs
PO Box 4112, Delivery Centre
Footscray West, 3012
Phone: 1300 GO DOGS (46 36 47)
Fax: 03 9680 6103

Footscray Football Club Limited
(Trading as Western Bulldogs)
ABN: 68 005 226 595.
Club Patron: Mrs Susan Alberti AM
Web: www.westernbulldogs.com.au

December 03, 2008

Lucy Parrington
C/O Dr Clare Mac Mahon
School of Human Movement, Recreation & Performance
Victoria University
PO BOX 14428
Melbourne, VIC 8001

Dear Lucy,

Thankyou for your request to collect data from the players of the Western Bulldogs Football Club for the research you are conducting on handballing technique and decision making in Australian Rules football.

I am happy to grant you approval to collect data from our organisation.

Sincerely,

James Fantasia
General Manager, Football

cc: Dr. Kevin Ball
Dr. Clare MacMahon

Western Bulldogs
PO Box 4112, Delivery Centre
Footscray West, 3012
Phone: 1300 GO DOGS (46 36 47)
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December 03, 2008

Lucy Parrington
C/O Dr Clare Mac Mahon
School of Human Movement, Recreation & Performance
Victoria University
PO BOX 14428
Melbourne, VIC 8001

Dear Lucy,

Thankyou for your request to use the Western Bulldogs training facility for the research you are conducting on handballing technique and decision making in Australian Rules football.

I am happy to grant you approval and access to use our facilities for the testing involved in this research project.

Sincerely,

James Fantasia
General Manager, Football
Western Bulldogs

cc: Dr. Kevin Ball
Dr. Clare MacMahon

Appendix F

The content within Appendix F is provided for the purpose of specifying any additional detail that may be pertinent to understanding some of the procedures used in the biomechanical studies that has not been provided within the study chapters.

General participant preparation

Participants were measured for height using a stadiometer and mass, using standard calibrated electronic scales. Preferred hand and foot were self-reported. Participants were requested to wear standard training apparel (training or football shorts/ skins, a training t-shirt/ singlet and training sneakers).

Participants were fitted with rigid body marker clusters and requested to move their body in similar movements to the task requirements during testing to check for range and comfort. Following this, an anatomical landmark identification procedure was conducted using the First Principles interface and digitising pointer tool to define virtual landmarks at key anatomical landmarks. The participant was required to stand in a static position for a static frame of data to be collected to store the virtual landmark information.

Motion analysis and data collection

Three-dimensional data were collected using an optoelectronic motion analysis system. Three Optotrak Certus (3D RMS error 0.15mm) position sensors were placed strategically around the laboratory to capture an approximate central area of 1.0 m x 1.5 m x 1.5 m. Optotrak position sensors recorded the position coordinates of infrared light emitting diodes (LED) that were used to determine a biomechanical model (shank, thigh, pelvis, trunk, upper arm, forearm, hand) during the handballing movements.

As the Certus system has a maximum sampling rate of 4600/ (n+2), where n is the number of active markers, a compromise was required on the number of markers used (n=38), segments analysed and sampling rate. Although 115 Hz was the maximum sapling rate possible, 100 Hz was chosen because it was more readily matched with 50 Hz video footage. Registration of the capture area was performed with calibration cube device (Figure E.1), fitted with 16 LED markers (four per side). Cube algorithms are located within the tool file, imported in the data capture operating software (First Principles, NDI). Movement of the cube about the capture area allows calibration of the x, y, z co-ordinates common to the three position-sensors within the three-dimensional volume used. Motion data of the LED's were simultaneously captured and stored through NDI First Principles under '#.c3d' format. Files were then imported into motion analysis and data processing software (Visual3D). Visual3D was used in the model building process, in applying the model to the dynamic trials and data analysis procedures.

Figure F.1: Calibration cube device.

Global reference system

For biomechanical Studies 2, 3 and 4 the centre of the capture area was positioned 5.5m from a stationary target, which sat 1.5m high behind a net that dropped from the laboratory ceiling. In study 4 (Chapter 5), the net was removed to allow the ball to contact the target.

A global coordinate system (GCS) was aligned with the origin on the left aspect of the starting point (6.5m from the target). At the origin, positive Z was directed vertically upward. The GCS was orthogonal, with the X-Y plane level with the laboratory floor. Positive Y was directed posterior to anterior in the direction of the target, positive X was directed left to right with respect to the direction of the handball task (Figure F.2).

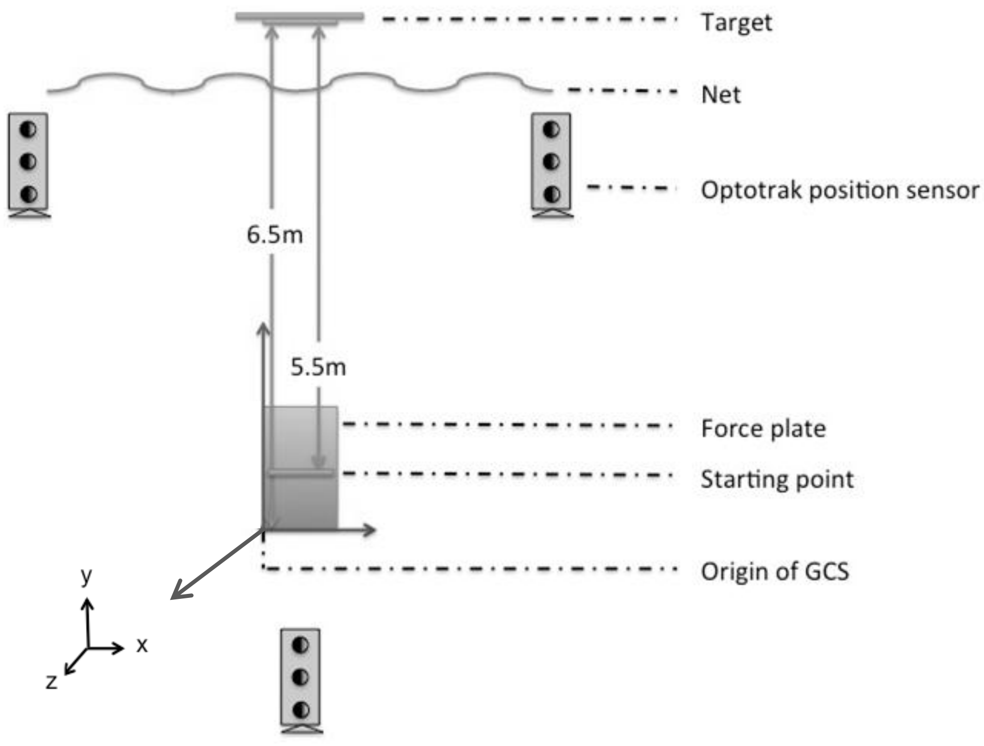

Figure F.2: Laboratory diagram and global coordinate system (GCS).

In Study 5 and 6, there were five targets placed in a star formation equally around the participant as described in Chapter 6 and 7. In this study the central capture area was 5 m from each target. The GCS was aligned such positive Y pointed toward one target, nominated as the front target. The participants' faced this target as their starting position for each trial, but focussed on the floor until the signal for movement was emitted.

Biomechanical model

The biomechanical model used was based on the Calibrated Anatomical Systems Technique (Cappozzo et al., 1995). Marker attachment was based on an under-wrapping technique (Manal et al., 2000). These procedures are believed to help minimise errors relating to surface movement and are commonly used within our laboratory because of their non-invasive and routine use within biomechanics research (Ball, 2011; Coventry et al., 2011; Parrington et al., 2012).

Marker set

Rigid body marker clusters

All markers were attached to rigid shells except for a single marker identifying the foot motion, which was located on the shoe at the lateral aspect of the 5^{th} metatarsal head. The rigid shells were custom shaped to fit the anthropometric standard contour of the participant populations' body segments using lightweight heat-mouldable plastic. These rigid bodies were created for the distal lateral aspects of the shank, thigh, upper-arm, forearm and the dorsal surface of the hand. Standard NDI smart marker rigid clusters were used for the upper and lower trunk (pelvis). A list of rigid clusters with associated individual markers is provided in Table F.1.

Table F.1

Rigid body clusters and respective LED markers

Cluster	Position	Marker label	Position of LED
Upper-trunk	In a position relative to C7	T1	Distal-left trunk cluster positioned below C7
		T2	Distal-right trunk cluster positioned below C7
		T3	Proximal trunk cluster positioned over C7
Right upper arm	Lateral aspect positioned in the distal third of the right upper arm	RUA1	Right superior upper arm cluster
		RUA2	Right distal-medial upper arm cluster
		RUA3	Right distal-lateral upper arm cluster
Left upper arm	Lateral aspect positioned in the distal third of the left upper arm	LUA1	Left superior upper arm cluster
		LUA2	Left distal-medial upper arm cluster
		LUA3	Left distal-lateral upper arm cluster
Right forearm	Distal aspect of right forearm positioned toward the posterior radial side	RFA1	Right superior forearm cluster
		RFA2	Right distal-medial hand cluster
		RFA3	Right distal-lateral hand cluster
Left forearm	Distal aspect of left forearm positioned toward the posterior radial side	LFA1	Left superior forearm cluster
		LFA2	Left distal-medial hand cluster
		LFA3	Left distal-lateral hand cluster
Right hand	Dorsal surface of the right hand	RH1	Right medial hand cluster
		RH2	Right lateral hand cluster
		RH3	Right distal hand cluster
Left hand	Dorsal surface of the left hand	LH1	Left medial hand cluster
		LH2	Left lateral hand cluster
		LH3	Left distal hand cluster
Lower-trunk (pelvis)	Positioned relative to the posterior superior iliac spine / sacrum	P1	Distal pelvis cluster
		P2	Right pelvis cluster (aligned with PSIS)
		P3	Left pelvis cluster (aligned with PSIS)
Right thigh	Lateral aspect positioned in the distal third of the right thigh	RT1	Right superior thigh cluster
		RT2	Right medial thigh cluster
		RT3	Right lateral thigh cluster
Left thigh	Lateral aspect positioned in the distal third of the left thigh	LT1	Left superior thigh cluster
		LT2	Left medial thigh cluster
		LT3	Left lateral thigh cluster
Right shank	Distal and lateral aspect of the right shank (5-10cm above distal tip of lateral malleolus)	RS1	Right superior-lateral shank cluster
		RS2	Right superior-medial shank cluster
		RS3	Right distal shank cluster
Left shank	Distal and lateral aspect of the left shank (5-10cm above distal tip of lateral malleolus)	LS1	Left superior-lateral shank cluster
		LS2	Left superior-medial shank cluster
		LS3	Left distal shank cluster
Right foot (single marker)		RTOE	Right lateral head of the fifth metatarsal
Left foot (single marker)		LTOE	Left lateral head of the fifth metatarsal

Velcro-hook tape was attached to the back of each of the rigid bodies. Three LEDs (NDI smart-markers) were attached to each rigid mould in a non-collinear array. These markers formed the triad of markers required to compose the technical coordinate system (TCS) of the cluster (Figure E.3).

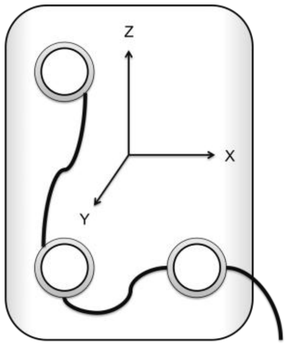

Figure F.3: Rigid marker cluster and technical coordinate system.

Technical coordinate systems were established for each rigid cluster using 6D Architect™ (NDI, Waterloo, Canada). The software records the positions of the smart markers attached to the rigid shells of each cluster set and then digitally embed the TCS according to the tracked markers. The TCS for the NDI standard cluster sets were imported from NDI.

Attachment of clusters

Specified sizes of elasticised neoprene with Velcro-loop were wrapped around each of the bilateral shank, thigh, upper-arm, forearm and hand to assist in the placement of the rigid bodies. The neoprene fabric was modified so that the rubber of the material was exposed and could grip to the skin to stop the cluster from slipping during testing. This method of attachment also allowed secure fastening of the rigid bodies, which had been fitted with Velcro-hook to the Velcro-loop of the neoprene. Once the rigid bodies were attached to the segment, an additional thin belt of elasticised neoprene was placed across the cluster and around the body segment to further minimise movement of the rigid body on the skin during testing (Figure F.4). Clusters and markers remained on the body for the length of the testing session.

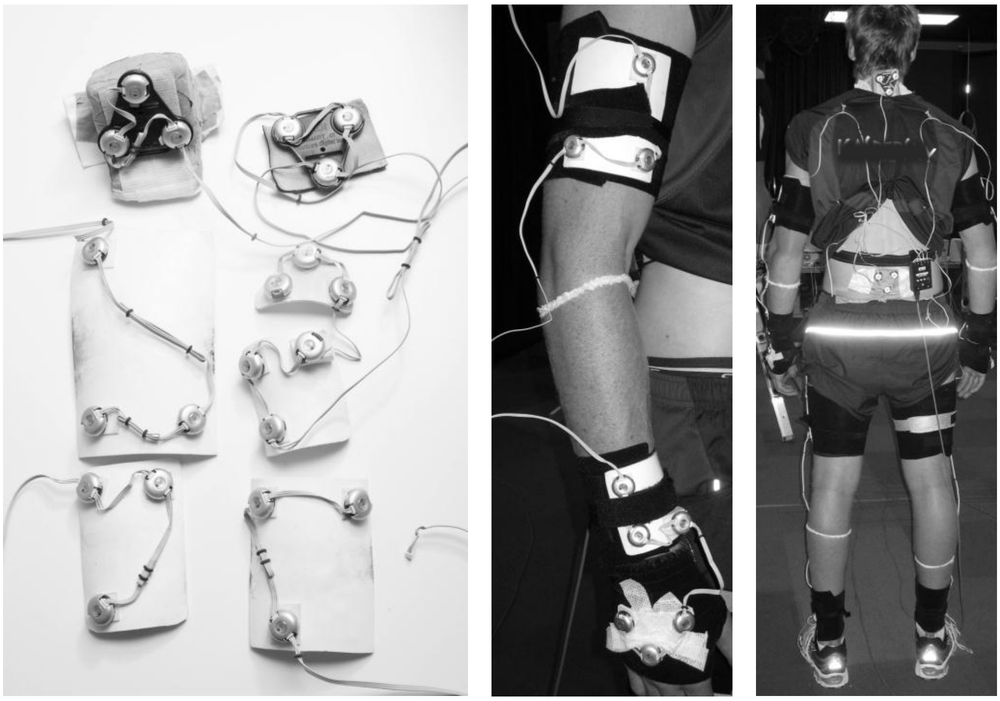

Figure F.4: Left: Marker clusters. Right: Clusters attached to participant.

The attachment of the upper and lower trunk clusters involved a different process. Neoprene Velcro-loop material was cut to the size of the pelvis rigid body and attached (with strong adhesive) to elastic hypoallergenic sports tape. The material was then applied over the posterior of the pelvis such that the pelvis cluster (Velcro-hook applied on posterior surface) could be attached with the two superior LED’s in line with the left and right Posterior Superior Iliac Spine (PSIS). A combination of rigid and elasticised sports tape was then used to further secure the pelvis marker cluster to the back (Figure F.5).

Figure F.5: Attachment of pelvis cluster.

To compensate for hip and trunk flexion that existed during the performance of the handball task, which caused marker occlusion, the trunk cluster was placed on a foam wedge to direct the LED's toward the position sensors throughout data capture. The wedge was created from inflexible foam cut to fit over C7. The wedge was further covered in rigid sports tape and Velcro-loop tape was adhered to the top surface. Similar to the method of attachment of the pelvis cluster, the wedge was super glued to elastic hypoallergenic sports tape so that it could be fitted to the body over the C7 vertebrae. The trunk cluster was affixed via the Velcro and then further sports tape was placed across the cluster and foam wedge to ensure it was securely fitted to the body (Figure F.6).

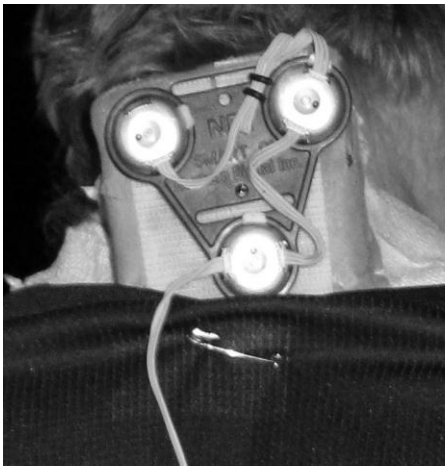

Figure F.6: Attachment of trunk cluster on neck.

Additional markers

One single LED was placed on the fifth metatarsal head. Sports tape was first applied to the players shoe over this anatomical landmark, and then the single LED marker was glued to this landmark.

Anatomical landmark identification procedures and static data collection

For each subject a static trial was used to build an associated biomechanical model, which was then applied to the dynamic handball trials data for processing.

Anatomical landmarks were used as the location of virtual markers during testing. This process required the use of NDI's digitising probe tool (Figure F.7). The end point location of the digitising probe was first identified through pivot procedures, a process that qualifies the digitising probe based on the probe's technical frame in 6D Architect™. Following this, NDI First Principles software was used to store the position of the virtual landmarks relative to the TCS of each rigid cluster (as per Cappozzo et al., 1995). Provided the triad of markers on the cluster that compose the TCS are all visible, the 3D location of the virtual markers can be referenced in space and determined during dynamic trials.

Figure F.7: NDI digitising probe tool used to digitise virtual markers at anatomical landmarks.

Anatomical landmarks were manually palpated, and then virtual markers at each of these anatomical positions were defined using the digitising probe. This method is advantageous as it eliminates the chance of maker displacement through skin movement that generally occurs about bony prominences (Della Croce, Leardini, Chiari, & Cappozzo, 2005), and removes the chance of knocking individual tracking markers off during trials. The anatomical landmarks used in this study are recognised by Cappozzo et al. (1995) as recognisable bony prominences and repeatable via manual palpation. The same researcher performed location and digitisation procedures for all participants.

All anatomical landmarks, virtual markers and their respective clusters are identified in Table F.2.

Table F.2

Virtual markers at defined anatomical landmarks relative to rigid body clusters

Cluster	Marker label	Location
Trunk	RLR	Lateral aspect of the Right 12^{th} Rib
	LLR	Lateral aspect of the Left 12^{th} Rib
	RAP	Right Acromion Process
	RAH	Right Anterior Humeral head
	RPH	Right Posterior Humeral head
	LAP	Left Acromion Process
	LAH	Left Anterior Humeral head
	LPH	Left Posterior Humeral head
Upper-arm	RME	Right Medial Epicondyle
	RLE	Right Lateral Epicondyle
	LME	Left Medial Epicondyle
	LLE	Left Lateral Epicondyle
Forearm	RMW	Right Ulna Styloid Process
	RLW	Right Radial Styloid Process
	LMW	Left Ulna Styloid Process
	LLW	Left Radial Styloid Process
Hand	R2MC	Right second metacarpo-phalangeal joint
	R5MC	Right fifth metacarpo-phalangeal joint
	L2MC	Left second metacarpo-phalangeal joint
	L5MC	Left fifth metacarpo-phalangeal joint
Pelvis	RASIS	Right anterior superior iliac spine
	RGT	Right greater trochanter
	RIC	Superior aspect of the right iliac crest
	LASIS	Left anterior superior iliac spine
	LGT	Left greater trochanter
	LIC	Superior aspect of the left iliac crest
Thigh	RMK	Right Medial Epicondyle
	RLK	Right Lateral Epicondyle
	LMK	Left Medial Epicondyle
	LLK	Left Lateral Epicondyle
Shank	RMA	Right Medial Malleolus
	RLA	Right Lateral Malleolus
	LMA	Left Medial Malleolus
	LLA	Left Lateral Malleolus

A one second static trial was captured prior to dynamic testing so that the TCS and virtual markers could later be processed to form the biomechanical model through the building process in Visual3D. Participants stood with feet shoulder-width apart and toes pointing forward. Upper arms hung naturally beside the trunk, with elbows flexed to 90 degrees and with palms facing inwards toward each other. This posture was standardised for all subjects to ensure consistency, such that inter-subject differences were minimal and any related errors were uniform throughout all data collected.

Virtual markers provided the means to define joint centres and bone segments. Capture of the static trial was conducted to store the virtual markers within the cluster TCS for each segment. The static trial was exported from NDI First Principles as a *.c3d file format and imported into Visual3D. Anatomical frames and joint centres were then defined using the model-building platform, based on the virtually stored anatomical landmarks of each segment. This process provides more meaningful movement data than the arbitrary segment TCS data. At least three anatomical locations were required to define the anatomical frame in order to establish the orientation matrices and position vectors of each anatomical segment. This allowed the instantaneous orientation and position of the anatomical frames to be available when the biomechanical model (model*.mdh) was applied to the dynamic handball data; permitting kinematic analysis of segments and joints. The definition of anatomical frames on TCS and ALs is a common biomechanical procedure (Benedetti, Catani, Leardini, Pignotti, & Giannini, 1998; Cappozzo et al., 1995) and has been reviewed in publications (Cappozzo, Della Croce, Leardini, & Chiari, 2005; Della Croce et al., 2005).

Joint centre definitions

All joint centres were calculated in Visual3D, in reference to the virtual anatomical markers, which were associated in the static/ dynamic capture to the rigid body clusters. Definitions of these joint centres and related virtual markers are presented in Table F.3.

Table F.3

Joint centre definitions (indirect from bony landmarks)

Cluster	Name	Location	
Shoulder	RSJC	$\frac{Lhumerus}{605} \times (0.413, -0.903, 0.121)$	(Fleisig et al., 1996)
	LSJC	$\frac{Lhumerus}{605} \times (-0.413, -0.903, 0.121)$	
Mid-shoulder		$\frac{1}{2} \times DISTANCE(RAP, LAP)$	
Elbow	REJC	$\frac{1}{2} \times DISTANCE(RLE, RME)$	
	LEJC	$\frac{1}{2} \times DISTANCE(LLE, LME)$	
Wrist	RWJC	$\frac{1}{2} \times DISTANCE(RLW, RMW)$	
	LWJC	$\frac{1}{2} \times DISTANCE(LLW, LMW)$	
Hip	RHJC	$\frac{1}{4} \times DISTANCE(RGT, LGT)$	(Weinhandl & O'Connor, 2010)
	LHJC	$\frac{1}{4} \times DISTANCE(LGT, RGT)$	
Mid-hip		$\frac{1}{2} \times DISTANCE(LGT, RGT)$	
Knee	RKJC	$\frac{1}{2} \times DISTANCE(RLK, RMK)$	
	LKJC	$\frac{1}{2} \times DISTANCE(LLK, LMK)$	
Ankle	RAJ	$\frac{1}{2} \times DISTANCE(RLA, RMA)$	
	LAJ	$\frac{1}{2} \times DISTANCE(LLA, LMA)$	

Location of the hip-joint centre

The hip joint centre was determined using the greater trochanter (GT) method. This method identifies the hip joint centre at 25% of the distance from the ipsolateral to the contralateral greater trochanter and has been recently evaluated against functional hip joint centre location methods (Weinhandl & O'Connor, 2010). The GT method of location was found to have a smaller total 3D difference with respect to the functional method (Schwartz & Rozumalski, 2005), in comparison with Bell's method (Bell, Pederson & Brand, 1990). It was decided due to the time constraints enforced with the elite sample used, that the GT method was the most appropriate locator of the hip joint centre. Following determination of the hip joint centre via the GT method, the left and right hip joint centres were stored in reference to the respective thigh cluster technical co-ordinate systems.

Location of the shoulder-joint centre

The modelling of the upper-arm (upper arm) has been inconsistent amongst both clinical and sport biomechanics literature. Although markers on anatomical landmarks, the lateral and medial epicondyles, to determine the elbow joint centre location are regularly used, methods surrounding the location of the shoulder joint centre (e.g. Drop methods: Schmidt, Disselhorst-Klug, Silny, & Rau, 1999; Rab, Petuskey & Bagley, 2002; Regression methods: Dillman, Fleisig, & Andrews, 1993; Anglin & Wyss, 2000; and functional methods: Rettig, Fradet, Kasten, Raiss, & Wolf, 2009) are even more divergent than the methods of locating the hip joint centre. Interestingly, in their position paper for the ISB, Wu et al. (2005) preferred not to standardise the definition of the centre of glenohumeral rotation, leaving it to the researchers discretion.

For the purpose of this study, shoulder joint motion was limited to the glenohumeral joint. Unlike overarm throwing movements (e.g. baseball pitching, American football passing, European football throwing, tennis serve, volleyball serve), the movement pattern involves predominantly flexion and extension, of which small errors in the location of the shoulder joint centre are believed to minimally influence this angular component, due to the relative length of the upper arm (Anglin & Wyss, 2000). The closed skill handball does not see the shoulder abducted to 90 degrees, and thus Gimbal lock is not considered an issue within the joint co-ordinate decomposition.

The underarm motion that occurs during the punching phase of the handball is similar to the downswing phase of the softball windmill pitch. In their study of softball windmill pitching, Werner et al., (2005) utilised Fleisig et al.'s approach (1996) to determine the shoulder joint centre. This approach has been well referenced at the

American Sports Medicine Institute and within a number of baseball studies. A modification of this method was used to locate the shoulder joint centre in this study, where the radius of the reflective marker was removed from the equation, given that the acromion marker was stored virtually, rather than an external marker. The static model was used to determine the bilateral shoulder joint centre and then this position was stored within the upper arm segment for each arm.

Segment definitions

The segment coordinate systems used to determine the kinematics from the biomechanical model used in this study are described in detail below.

Upper-trunk

The origin of the trunk was defined as the mid-point between the right and left shoulder joints. The positive Z axis ran from the midpoint between the right and left iliac crest marker up through the origin. The positive X axis was directed left to right, perpendicular to the Z axis. The positive Y axis was orthogonal to the frontal (Z-X) plane.

Upper arm

The proximal end point of the upper arm was defined as the shoulder joint centre. The distal end point was defined as the elbow joint (mid-point of the medial and lateral elbow virtual markers). The frontal plane was defined by the shoulder joint centre and the virtual anatomical markers on the medial and lateral epicondyles of the upper arm. The positive Z axis was directed along the long axis of the upper arm (distal end to proximal end) from the elbow joint to the shoulder joint. The positive X axis ran from the medial to lateral epicondyle for the right arm and from lateral to medial epicondyle in the left arm. The positive Y axis was anteriorly directed and perpendicular to the frontal (Z-X) plane. The origin is established at the shoulder joint and located along the Z axis.

Forearm

The frontal plane of the forearm was defined by a least squares approach applied such that the sum of squares distance between the medial and lateral epicondyles of the elbow and the ulna and radial styloid processes and the frontal plane was minimised. The positive Z axis ran from the wrist joint centres to the elbow joint centres. The positive X axis ran from the ulna styloid process to the radial styloid process on the right arm and the radial to ulna styloid process on the left arm. The positive Y axis ran anteriorly and perpendicular to the frontal plane. The origin was defined at the elbow joint centre, located in line with the Z axis.

Hand

The frontal plane of the hand was defined by a least squares approach applied such that the sum of squares distance between the ulna and radial styloid processes and the second and fifth metacarpo-phalangeal joints and the frontal plane was minimised. The positive Z axis ran from the mid-point between the second and fifth metacarpo-phalangeal joints to the wrist joint centres. The positive X axis ran from the fifth to the second metacarpophalanjeal joint for the right hand and vice-versa for the left hand. The positive Y axis ran anteriorly and perpendicular to the frontal (Z-X) plane. The origin was defined along the line of the Z axis at the proximal end – the wrist joint centre.

Lower-trunk (Pelvis)

The origin of the pelvis was defined as the mid-point between the right and the left iliac crest virtual markers. The positive Z axis was directed from the mid-point between the right and left iliac crest upward through the origin. The positive X axis ran in the direction from the left iliac crest to the right iliac crest. The Y-axis was anterior and orthogonal to the Z-X plane (Figure F.8).

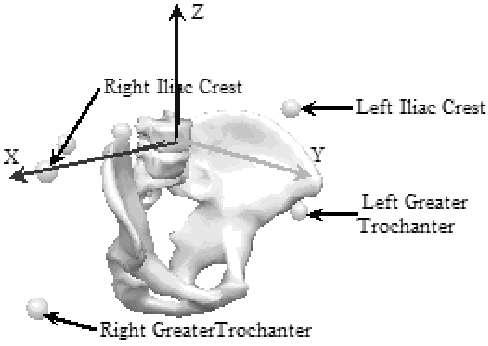

Figure F.8: Representation of the lower-trunk (pelvis segment, Visual3D, C-motion Inc.).

Thigh

The proximal end point of the thigh was defined by the hip joint centre, and the frontal plane was defined by this point and the medial and lateral epicondyles of the femur. The distal end point was defined as the knee joint (mid-point of the medial and lateral epicondyles of the knee). The positive Z axis was directed up the long axis of the femur (distal end to proximal end) from the knee joint to the hip joint. The positive X axis ran from the medial to lateral epicondyle for the right leg and from lateral to medial epicondyle in the left leg. The positive Y axis was anteriorly directed and perpendicular to the frontal (Z-X) plane. The origin is established at the hip joint and located along the Z axis (Figure F.9).

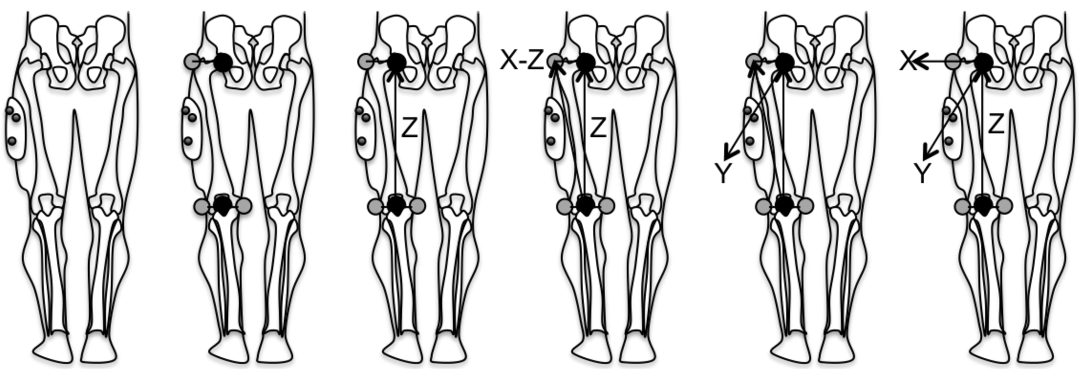

Figure F.9: Construction of the thigh anatomical frame (adapted from C-Motion, Inc.).

Shank

The frontal plane of the shank was defined by a least squares approach applied such that the sum of squares distance between the medial and lateral epicondyles of the knee and the medial and lateral malleoli of the ankle and the frontal plane is minimised. The positive Z axis ran from ankle joint centre to the knee joint centre. The positive X axis ran from the medial to lateral epicondyle on the right leg and from lateral to medial epicondyle on the left leg. The positive Y axis ran anteriorly and perpendicular to the frontal (Z-X) plane. The origin was defined at the knee joint centre, located in line with the Z axis.

Joint coordinate systems

Joint co-ordinate systems (JCSs) provide a functional representation of 3D joint kinematics by means of delineating the order of rotations between two adjacent anatomical frames, or anatomical frame and GCS. Visual3D computes joint attitude through Cardan angles, which are sequence dependent. This method has been described as equivalent to the Grood and Suntay (1983) JCS ($\hat{e}_1$ - flexion-extension axis in the proximal segment; $\hat{e}_3$, long axis of the distal segment; and $\hat{e}_2$ - floating axis/ ad-abduction), when ALs have been used in testing, provided the sequence of rotations has been pre-defined (Cole, Yeadon, Nigg, & Ronsky, 1993).

The default Visual3D calculations are based upon a Cardan X-Y-Z sequence. This specified the first rotation about the x axis (medio-lateral axis of the proximal segment; equivalent to $\hat{e}_1$), the second rotation about the y axis (the nodal axis between the two segments; equivalent to $\hat{e}_2$) and the last rotation about the z axis (the long axis of the distal segment; equivalent to $\hat{e}_3$). This corresponded to flexion/ extension, adduction/ abduction and axial rotation of the moving anatomical frames with respect to the fixed anatomical frame or GCS, according to the anatomical definitions of the upper and lower extremity segments. This provides a set of three independent angles obtained by an ordered sequence of rotations (a, b, c) about the three axes embedded in the proximal segment Cartesian coordinate system to obtain the attitude of the distal segment coordinate system (Baker, 2001; Cappozzo et al., 2005; Cole et al., 1993). This adheres to recommendations of the International Society of Biomechanics (ISB; Wu & Cavanagh, 1995). In this thesis, the motions of interest and their definitions can be found in Chapter 4, Table 4.1.

The composite range of motion available within the shoulder complex makes definition of the joint coordinate system problematic. Although recommendations have been made (Wu et al., 2005), definitions generally lack standardisation, creating difficulties for the presentation of anatomically meaningful data. This study focused on the movement occurring in the glenohumeral joint only, and was defined by the link between the trunk and the upper arm. Within their ISB recommendations, Wu et al. (2005) suggested a Z'-Y-Z'' order of rotations to adjust for computational issues associated with gimbal lock. In this sequence, the first Z axis is fixed to the trunk, and coincident with the Z axis of the trunk segment coordinate system. This sequence is not conductive to a movement that is predominantly constrained about the X axis in a position less than 90 degree abduction, because the first order of rotations relates to horizontal ab-/adduction. Though variations of the handball may occur within the open context of the game, the most commonly executed skill was a forward hand pass (Parrington et al., 2013b [Chapter 2 of this thesis]), which involved principally shoulder extension (backswing) and shoulder flexion (swing phase), a movement that is not subject to the analytical complications relating to gimbal lock (Anglin & Wyss, 2000). In accordance, the Cardan X-Y-Z sequence was used for all shoulder joint motion.

Predominant movements for the lower-trunk are about the z-axis, making a Cardan Z-Y-X order of rotations (rotation-obliquity-tilt) more a more easily interpretable description of segment motion (Baker, 2001), and this sequence has been applied previously (e.g. Kang & Dingwell, 2006). This same sequence was used to describe motion of the trunk and the movements between the trunk and the pelvis.

Dynamic testing

All dynamic testing information is provided within the thesis chapters that include biomechanical analysis.

Data processing

Interpolation

Due to the dynamic nature of the handball, a number of marker occlusions occur throughout the performance of the skill; requiring gaps in the position tracking of the active LED markers to be interpolated. Gaps in the raw data of up to 5 frames (0.05 seconds) were fitted using a third order polynomial, using two frames prior to and post gap used to calculate the coefficients of the polynomial (Visual3D). Position-time graphs from interpolated trials were compared with raw data of trials with no marker occlusion for each participant to ensure interpolation had not caused anomalies. Data were also screened for each event and phase of data output. In the instance of datum uncertainty, the datum was removed from further processing.

Event determination and creation

Each event was determined through pipeline processing in Visual3D. Where marker occlusion affected the determination of events, and visual inspection of the data did not allow identification of common points on position-time or velocity-time curves, the event was excluded in the trial and any data based on that event was removed as a result. This rarely affected maximum backswing (involved in ROM) or ball contact.

Lead foot toe-off was determined by the vertical displacement of the foot exceeding a 0.05 m threshold and the change in anterio-posterior velocity of the toe marker on the leading (front) leg.

Initiation of backswing

Initiation of backswing was determined through threshold values of the punching limb, whereby the punching limb crossed a zero threshold in the anterior-posterior direction, indicating that the limb began to move in a posterior direction.

Maximum backswing

Maximum backswing was determined through the velocity of the punching hand crossing a threshold of zero m/s in the vertical direction and posterior direction, indicating a change in direction from upwards to downwards, and from backwards to forwards. The event was determined first through the threshold of the vertical direction. Where players did not meet this threshold vertically, the anterio-posterior threshold was assessed.

Ball contact (BC)

As ball contact could not be visualised through three-dimensional data, it was determined through a combination of the assessment of absolute maximal velocity of the hand, distance threshold between the support and punching hand and crosschecked through visual footage.

Backswing phase

The backward swinging motion of the punching arm and hand from the onset of backswing to maximum backswing

Swing phase

The forward swinging motion of the punching arm and hand from maximum backswing to ball contact

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