Muscular strength, fitness and anthropometry in elite junior basketball players

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STUDENT DECLARATION

"I, Eric Drinkwater, declare that the PhD thesis entitled *Muscular strength, fitness and anthropometry in elite junior basketball players* is no more than 100,000 words in length, exclusive of tables, figures, appendices, 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."

Eric Drinkwater

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THESIS ABSTRACT

Basketball is a sport with many complex demands that require a combination of fitness, skills, team tactics and strategies, and motivational aspects. However key areas that are likely to play an important role in a basketball player's success are muscular strength, fitness and body size. Methods of evaluating and developing these characteristics have been extensively tested in controlled research settings, but there is a dearth of research exploring the value of, and methods of improving, muscular strength, fitness and body size of basketball players within the demanding schedule of an elite junior development program. These were therefore explored in this thesis.

Study 1 Concerns about the value of physical testing and apparently declining test performance in junior basketball players prompted a retrospective study of trends in anthropometric and fitness test scores related to recruitment age and recruitment year. Players were 1011 females and 1087 males entering Basketball Australia's State and National programs (1862 and 236 players respectively). Players were tested on 2.6 ± 2.0 (mean ± SD) occasions over 0.8 ± 1.0 y. Test scores were adjusted to recruitment age (14-19 y) and recruitment year (1996-2003) using mixed modeling. Effects were estimated by log transformation and expressed as standardized (Cohen) differences in means. National players scored more favorably than State players on all tests, differences being generally small (standardized differences, 0.2 – 0.6) or moderate (0.6 – 1.2). On all tests, males scored more favorably than females, with large standardized differences (>1.2). Athletes entering at age 16 performed at least moderately better than athletes at 14 y on most tests (standardized differences, 0.7 - 2.1), but test scores often plateaued, or began to deteriorate when entering at ~17 y. Some fitness scores deteriorated over the 8-y period (1996-2003), most notably a moderate increase in sprint time and moderate (National male) to large (National

female) declines in shuttle-run performance. Variation in test scores between National players was generally less than that between State players (ratio of SD, 0.83 - 1.18). More favorable means and lower variability in higher-level athletes highlights the potential utility of these tests in junior basketball programs, though secular declines in fitness should be a major concern for Australian basketball coaches.

Study 2 These findings prompted further investigation into the magnitude of changes in individual player fitness and anthropometric test scores between phases of a year and over multiple years. Detailed information on the direction and magnitude of training-induced changes in fitness in a within-subject design is essential for basketball coaches to evaluate and prescribe conditioning programs. Mixed modeling was used to estimate mean changes within and between seasons, and to estimate individual variability as the standard deviation of change scores between assessments. Changes were expressed as standardized (Cohen) effect sizes for interpretation of magnitudes (trivial <0.2; small 0.2-0.6, moderate 0.6-1.2). In the first 2 y National and State males showed small longitudinal improvements in body mass, skinfolds, and shuttle-run performance (effect size 0.28 – 0.42). After 2 y National females made small improvements in most tests (0.27 – 0.42), but National males showed a small decline in shuttle-run performance (0.55). Other changes in mean test scores within and between seasons were trivial. Individuals showed small to moderate variability about the mean change between phases (0.23 – 0.87) and between years (0.26 – 1.03), with State-level players having greater variation in all tests (State/National ratio 1.1 – 2.4). Coaches or sport scientists monitoring or modifying fitness of basketball players should recognize there is generally little overall change in mean fitness within and between seasons. They should also take into account the small to moderate changes in individuals. While fitness training programs for athletes with dedicated needs are relatively well supported in the literature, there is very limited peer-reviewed literature to assist the resistance training coach in developing body size, strength, and power of team-sport athletes.

Study 3 Most high-level basketball players participate in an organised resistance training program to improve muscular strength, fitness, and body size. Bench press is one of the most commonly performed resistance training exercises, and there are many different training philosophies revolving around manipulation of different components of the bench press mechanics. During the concentric movement of the bench press, there is an initial high-power push after chest contact, immediately followed by a characteristic area of low power, the so-called “sticking region”. During high-intensity lifting, this decline in power can result in a failed lift attempt. The purpose of this study was firstly to determine the validity of an optical encoder to measure power, and secondly to employ this device to determine power changes during the initial acceleration and “sticking region” during fatiguing repeated bench presses. Twelve highly trained junior basketball players performed a free-weight bench press, a Smith Machine back squat, and a Smith Machine 40 kg bench press throw for power validation measures. All barbell movements were simultaneously monitored using videography and an optical encoder. Eccentric and concentric mean and peak power were calculated using time and position data derived from each method. Validity of power measures between the video (criterion) and optical encoder scores were evaluated by standard error of the estimate (SEE) and coefficient of variation (CV). Seven subjects then performed four sets of six bench press repetitions progressively increasing from 85 to 95% of their 6 repetition maximum, with each repetition continually monitored by an optical encoder. The power SEE ranged from 3.6 to 14.4 W (CV, 1.0-3.0%; correlation, 0.97-1.00). During the bench press training, peak power declined by ~50% ($p<0.05$) during the initial acceleration phase of the final two repetitions of the final set. While decreases in peak power of the sticking point were significant ($p<0.05$) as early as repetition six (-42%) they reached critically low levels in the final two repetitions (~ -95%). In conclusion, the optical encoder provided valid measures of kinetics during free-weight resistance training movements. The decline in power during the initial acceleration phase appears a factor in a failed lift attempt in the sticking point in highly trained junior basketball players.

Study 4 The power loss in the first phase of the bench press only becomes a limiting factor when the loss of power in the sticking point leads to lift failure. Therefore, training to the point of failure may be an important stimulus for generating sufficient power in the first phase of the bench press to successfully press through the sticking point. This study investigated the importance of training leading to repetition failure in optimising the performance of elite junior athletes in two different tests: six-repetition maximum (6RM) bench press strength and 40kg bench throw power. Subjects were 26 elite junior male basketball (n=12, age 18.6 ± 0.3 y, height 202.0 ± 11.6 cm, mass 97.0 ± 12.9 kg) and soccer (n=14, age 17.4 ± 0.5 y, height 179.0 ± 7.0 cm, mass 75.0 ± 7.1 kg) players with a history of greater than six months strength training. Subjects were initially tested twice for 6RM bench press mass and 40kg Smith Machine bench throw power output (W) to establish retest reliability. Subjects then undertook bench press training three sessions per week for six weeks, using equal volume programs (24 total repetitions x 80-105% 6RM in 13 min 20 s). Subjects were assigned to one of two experimental groups designed to either elicit repetition failure with four sets of six repetitions every 260 s (RF_{4x6}) or allow all repetitions to be completed with eight sets of three repetitions every 113 s (NF_{8x3}). The RF_{4x6} treatment elicited substantial increases in strength (7.3 ± 2.4kg, +9.5%,

$p<0.001$) and power (40.8 ± 24.1 W, +10.6%, $p<0.001$), while the NF_{8x3} group elicited 3.6 ± 3.0kg (+5.0%, $p<0.005$) and 25 ±19.0 W increases (+6.8%, $p<0.001$). The improvements in the RF_{4x6} group were significantly greater than the repetition rest group for both strength ($p<0.01$) and power ($p<0.05$). Bench press training that leads to repetition failure induces greater strength gains than non-failure training in the bench press exercise for elite junior team sport athletes.

Study 5 Strength improvements are greater when resistance training continues to the point where the individual cannot perform additional repetitions (i.e. repetition failure). Performing additional forced repetitions after the point of repetition failure to further increase the set volume is a common resistance training practice. However, whether increasing the number of forced repetitions increases the magnitude of strength development is unknown and was investigated here. Twenty two team-sport athletes trained for six weeks completing either 4x6, 8x3, or 12x3 (sets x repetitions) of bench press. The 4x6 and 12x3 protocols increased the number of forced repetitions by respectively increasing work intervals or volume compared to the 8x3 group. Subjects were tested on 3- and 6-repetition maximum (RM) bench press (81.7±9.9 and 76.2±9.2 kg respectively, mean ±SD), and 40kg Smith Machine bench press throw power (756±156 W). The 4x6 and 12x3 groups had more forced repetitions per session ($p<0.01$) than the 8x3 group (4.4±0.9 and 3.6±0.8, and 2.0±0.5 repetitions). As expected, all groups improved 3RM (4.6 kg, 95% Confidence Limits: 3.2-6.1), 6RM (4.9 kg, 3.3-6.5), bench throw peak power (59 W, 23-95), and mean power (23 W, 4-42) (all $p<0.01$). There were no significant differences in strength or power gains between groups. In conclusion, when repetition failure was reached, neither additional forced repetitions, nor additional set volume further improved the magnitude of strength gains. This finding questions the efficacy of these current common strength training practices.

Conclusions The quality of key fitness and anthropometric test scores of Australian junior basketball players showed evidence of decline over a 7 yr study period despite the importance of fitness and body composition to basketball. Fortunately, there is sufficient individual variation in changes in fitness and anthropometry test scores to indicate that substantial improvements are possible with an appropriate training program. As a method of improving fitness, the bench-press resistance training model, consisting of two separate six-week training programs equal in volume and training time but differing in the amount of fatigue, showed that training to the point of repetition failure elicited greater strength adaptations than non-failure training. Refinement of the training protocol allowed further comparison of the effects of additional training volume and a greater number of forced repetitions. Taken together these experimental findings support the notion that training to the point of repetition failure is an important component of a periodized training program for strength development. However six weeks of training using forced repetitions with the assistance of a spotter conveyed no further benefit to strength, power, or hypertrophic adaptations. Additional research is required to verify whether the transfer of these upper body adaptations apply to lower-body activities such as squats, and whether high intensity short term strength and conditioning programs can improve power output enough to have a substantial positive impact on basketball-specific skills such as running and jumping.

CHAPTER 1: THESIS INTRODUCTION

Basketball involves approximately 450 million registered participants from over 200 national federations belonging to the Fédération Internationale de Basketball (FIBA) [1]. The monetary value of basketball is substantial, particularly in the professional leagues, with the 30 teams in the 2004/05 National Basketball Association (NBA) season in the USA paying its 480 players $US1.68 billion in salaries alone. With considerable international, national, and local pride associated with winning, and the monetary rewards available, it is somewhat surprising to find very little published research on basketball preparation and training. Basketball federations, teams, coaches, players and support personnel are all interested in enhancing the performance of teams and players to improve the likelihood of competitive success. The 2003-2004 NBA regular season had an average point spread of 10.3 ± 6.6 points, indicating that the competitive edge would not need to be large to make a difference between winning and losing a game.

A key factor underpinning the dearth of research in team sports is the complexity of quantifying the important elements of these sports [301]. Intermittent, high-intensity team sports such as the court sports (e.g. basketball, volleyball, netball) and field sports (e.g. football, field hockey) have many complex demands that require a combination of fitness, skills, team plays, tactics and strategies, and motivational aspects [301]. Despite these complexities, it seems likely that a key area that plays an important role in basketball success is a player's physical fitness and body size [302]. The modern game of basketball has evolved to the point where tall, heavy players are preferentially recruited to key positions close to the basket, while faster and more agile players are chosen for perimeter positions. As of the year 2000, FIBA has introduced rules to make the offence more dependent on rapidly unfolding plan of attack to increase spectator excitement, thereby increasing a player's need for speed and fitness. Rule changes included reducing the time allowed for the offensive team to move the ball forward into the offensive court from 10 s to 8 s, and reducing the maximum time allowed for offence to shoot the ball once they take possession from 30 s to 24 s. To demonstrate the importance of strength, power, and muscle mass to basketball players, anthropometric and fitness test scores have been previously linked with basketball level of play [211], individual player success [14, 134], playing time [140], position [191], and team success [113]. These research outcomes and the practical experience obtained on court has increased the interest of coaches in the size and physical fitness of their players [78].

Given the importance of strength, power, and muscle mass to basketball, players are often prescribed a resistance-training program. While many basketball players participate in resistance training, the rationale for this element of the physical preparation is widely debated. Research conducted on resistance trained athletes such as bodybuilders, Olympic lifters, or powerlifters, typically examines dedicated programs focusing exclusively on hypertrophy, power, or strength development, given these are athletes with dedicated or specialist needs [178, 199]. Team sport athletes, such as an American football lineman [216], a basketball centre [36, 191], or a rugby forward [88], require a balance of strength, power, and hypertrophy for success, and have different requirements to the specialist needs of athletes such as powerlifters or bodybuilders. In order to develop new ideas in resistance training, researchers and practitioners must first have a clear understanding of the physiological mechanisms responsible for strength and power development. Unfortunately, the high training volume and intensity performed by elite team sport athletes may increase the risk of overuse injuries, even when the athletes are carefully monitored by a medical team of health professionals [283]. As a result, investigations studying the effects of a training intervention often study resisted movements that are not necessarily specific to the sport [193].

The initial purpose of this thesis is to quantify magnitudes of changes in anthropometric and fitness test results within individual athletes, and differences between groups of athletes of different genders (i.e. male or female), levels (i.e. State or National), calendar years (i.e. 1996, 1997, 1998, etc.), and ages (i.e. 14 – 19 years). Differences between genders and ages, and changes within athletes will be useful to the basketball community in designing fitness training programs individualised for specific athletes. Differences between athletes of different levels will be useful in establishing the potential for using physical testing results as a talent identification tool. Additionally, differences between calendar years will be useful in identifying any changes necessary in recruitment patterns to target recruit players of different sizes and fitness levels. Since resistance training is widely used in team sports, Subsequent studies in the thesis will validate a tool for measuring kinetic and kinematic properties during free-weight and isoinertial resistance training to identify potentially useful characteristics of bench press for developing a player's strength and power. These kinetic and kinematic properties will then be used to identify a time efficient bench press training program suitable to improve strength, power, and muscle mass in team sport athletes during their lead-up to major competitions (e.g.

2003 Junior World Basketball Championships, qualifying rounds for the 2004 Athens Olympic Games in volleyball).

CHAPTER 2: REVIEW OF LITERATURE

2.1 Introduction

Athletes involved in court and field team sports face a broad range of challenges that involve physical fitness, precision motor skills, team tactics, and individual and group motivation. When an opposing team is then encountered, the difficulties in quantifying any of these challenges are compounded as one team affects the intensity and tactics that the other team must use. During a game of basketball, individual player movements consist of repeated bouts of short accelerations that are seldom directly forward or in a straight line [209]. Clearly, basketball competition involves many high-intensity efforts with frequent breaks [209] necessitating high levels of fitness with a high capacity to recover during short rest intervals. The dynamic nature of high-intensity, intermittent team sports such as basketball makes research more difficult compared with the more uniform demands of individual sports such as running, swimming, cycling and rowing [36]. With only a few exceptions [141, 151, 293] the physiological-based research in basketball has traditionally focused on simple cross-sectional evaluation of player fitness and body composition.

There is little doubt that the modern game of basketball has evolved to a point where a player's fitness and body size play a pivotal role in team success [228]. Many professional basketball coaches and sport researchers have subjected basketball players to different batteries of physical tests to assess their anthropometric and fitness characteristics [14, 36, 113, 134, 138, 140, 141, 151, 172, 190, 191, 211, 293, 302]. Results of these studies generally reflect the moderate to high importance of endurance, speed, and anthropometric characteristics in basketball, despite the limited nature of these studies due to low sample numbers [138, 141, 293], and simple descriptive and inferential statistical analyses [6, 7, 284, 302].

While tests of power have clear specificity to basketball, the value of aerobic fitness may be questionable. In one study [140], the authors illustrated a moderate but non-significant negative correlation of 1.5-mile to playing time in the first of the four seasons assessed. In the next year there was a negligible and non-significant correlation, and in the next two years there was a high and significant positive correlation. Hoare [134] compared the 'best' versus the 'rest' basketball players on various components of fitness and found that depending on player position there was either no difference (2 out of 5 positions) or substantial differences (3 out of 5 position) in aerobic fitness. Furthermore, several studies have indicated improvements in aerobic fitness over a basketball season or competitive year [47, 293] (Table 2.2). Therefore, while some may question the value of aerobic fitness to basketball performance, there is supporting evidence for its value.

To improve a basketball player's fitness, fitness training programs that include resistance training have been implemented in order to improve power output [141-143, 275]. Resistance training programs are often constructed on the principle of 'specificity', that in order for training to assist a sport-specific movement, the exercise tasks must be similar to that movement both in velocity and movement pattern [32]. As described by the force-velocity curve [162], heavy resistance exercises must be performed slowly, and consequently to maximise movement velocity and power, resisted movements in power specific training are typically of lower resistance (i.e. 30-60% of a subject's maximal single repetition maximum, or 1RM) relative to strength training (i.e. >80% 1RM) [75, 128, 160, 169, 220]. Velocity- or power-specific training methods unfortunately neglect the importance of developing strength in order to develop power [44, 75, 196]. Consequently recent research has investigated combinations of both high and low resistances to optimise power training [18, 73, 75, 128, 160]. While combination and low resistance training can be effective in improving power they are often complex and difficult to prescribe in regular weight-rooms without specific equipment. More frequently prescribed in resistance training programs are traditional strength programs involving high resistances with 'forced repetitions' [288]. Scientific assessment of the value of performing repeated repetitions with the assistance of a spotter (i.e. forced repetitions) has been complicated by the difficulties in controlling experimental groups for certain training variables such as training volume, work performed, power output, and time under tension [288]. This thesis will examine fitness and anthropometric tests used to assess basketball players, the importance of fitness and body size in basketball, and the applications of high-fatigue heavy resistance training by team sport athletes to improve speed, strength, and hypertrophy.

2.2 Physical Testing Of Fitness And Anthropometry

2.2.1 Importance of Body Size and Fitness for Basketball

To optimise the necessary combination of body size and fitness on the court, coaches select players with different attributes for different positions. Modern basketball strategies place tall, strong players close to the basket and faster, more agile players in perimeter positions [301, 302]. This strategy allows the offensive team to quickly move the ball down the court as the larger, stronger players position themselves close to the basket for high percentage shots on the basket [221]. This universally accepted strategy in basketball implicates anthropometric and fitness characteristics in individual player success [14, 134], playing time [140], position [191, 302], and team success [114]. Hoare [134] concluded that anthropometric and fitness tests accounted for ~40% in variance of playing performance, while Hoffman *et* al. [140] reported that fitness test scores accounted for up to 20% of playing time when the athlete was well known to the coach or up to 80% if the athlete was not known. Trninic [302] demonstrated the success of larger players in executing skills close to the basket, such as rebounds and blocked shots, while smaller players are more successful in perimeter skills, such as assists and 3-point shooting. While the skill component also plays a vital role in basketball success [173], there are very important interactions between body size, physical fitness, and position-specific skill performance [14].

The findings that size and fitness are important to basketball success are intuitive to the basketball coaching community and underpin the interest of coaches in the optimal development of muscularity and physical fitness of their players. The necessity for high levels of fitness has been demonstrated by McInnes *et al*. [209] who studied basketball players in the Australian professional National Basketball League (NBL) using time-motion analysis. They showed that maximal efforts constituted 15% of a player's playing time, and the type of activity changed intensity or direction every 2.0 s. Furthermore, 75% of playing time was spent at greater than 85% of maximal heart rate with an average of 168 beats per minute, while the average blood lactate concentration was 6.8 mM, with an average maximum among players of 8.5 mM. Despite these indicators of high-intensity efforts, only 56% of a player's total time on the court was actually spent in live play. Clearly, there is a need to be able to perform high capacity work and recovery quickly between bouts.

While the relationship between the results of physical testing to a player's success has been demonstrated, the question has been raised if physical testing can be used as a tool for identifying potential talent in basketball [14, 134]. An obvious example of using height to select players is demonstrated in the rapidly increasing size of players in the American-based National Basketball Association (NBA), particularly in the decade between 1980 and 1990, in which the number of players over 7 feet (213 cm) tall rose from ~3.5% to ~11% [228]. Norton and Olds [228] modelled height and body mass against dollars earned and found that in 1993, for every 1.0 cm or 1.3 kg of the player, the player earned $US43,000 in additional payments over the playing career. Norton and Olds [228] also concluded that most internationally-born players in the NBA are recruited on the basis of their body size, since American-born players averaged 200 cm tall and weighed 99 kg, while internationally-born players averaged 211 cm and 110 kg. This conclusion also applied to the Women's National Basketball Association (WNBA) where US-born players averaged 181 cm and 73 kg while internationally-born players averaged 187 cm and 78 kg [228]. Clearly, body mass and height are critical elements in basketball success, regardless of the player being male or female, with increasing importance in recent years. This importance is possibly linked to the growing specialization of positions within the game of basketball in that the largest players spend relatively little time running and jumping, and also the increasing dominance of the so-called American style of play that is much more dependent on physical contact between players.

2.2.2 Fitness Testing for Basketball

Fitness and body size in team sports are relative to not only team-mates but opponents as well. To provide coaches and athletes with a reference point for comparison, there are several anthropometric and fitness tests commonly employed by basketball programs [284]. Most tests of body composition include height, body mass, and body fat, in addition to tests of aerobic fitness, jumping, and sprinting [127, 191, 280, 284]. Tests of strength are often also included [62, 141, 151, 275]. However, well controlled physiological and exercise performance research in team sports is rarely reported in the scientific literature and the existing research lacks studies with large sample sizes [138, 141, 293]. Very few studies go beyond one year [151, 190], or have greater than 100 athletes [36, 172, 191]. Pooling data on a small number of athletes over long periods of time has been accomplished [140, 151] though variation in measurement techniques can make the aggregation of large amounts of data from different sources difficult [191]. Most studies also tend to use basic forms of descriptive statistics [7, 284, 302], mainly because a small sample size and lack of homogeneity of variance can preclude the use of high-power statistical methods. Small sample sizes result in a higher likelihood of sampling error, while inconsistent test protocols often arrive at a single conclusion derived from different testing methods, such as deriving a category for “running speed” from a range of different running sprint times [191]. Basic statistics describe a specific study sample but are not always conducive to generalizing to a population. Many studies have reported descriptive measures of mean and standard deviation on specific samples, occasionally with p-values to discern the nature of differences between groups, but not confidence limits to indicate the precision of estimates for generalizing to a population [7, 36, 151, 172, 190, 191]. Nationally agreed testing protocols, such as those established in some countries [284] or associations [127], would allow compiling large amounts of data to permit a large scale, detailed analysis of fitness characteristic of different ages, genders, levels of play, or secular changes over long periods of time. These differences are largely unexplored yet remain critical issues for coaches and strength and conditioning staff in preparing and individualizing fitness training programs for higher level basketball.

There are concerns among Australian basketball coaches that Australian junior basketball players have been smaller, and of a lower fitness standard, in recent years (Landon, L. General Manager, National Teams & Competitions, Basketball Australia, personal communication). Basketball Australia (BA) has been collecting and storing results from a standardised battery of physical tests on all players entering its State and National junior programs. The testing has been designed to assess a player's physical fitness for basketball. Physical testing involved periodic assessment of vertical countermovement jump height, 20-m sprint time, and aerobic fitness, in addition to standing height, body mass, and skinfold assessment [284]. Basic descriptive analysis of physical test results conducted on Australian junior basketball players is illustrated in Table 2.1. In light of having physical test records accurately stored since 1996, systematically investigating trends in player body size and fitness is possible.

This thesis initially sought to describe the magnitudes of differences in physical test results between male and female Australian junior basketball players competing in National and State levels on a very large sample of players collected over several years (1996 - 2003), and determine whether physical test scores have changed substantially in more recent years. This approach will enable sport scientists to quantify the importance of fitness in discriminating between different levels of junior basketball players, and clarify whether the perception of coaches regarding declining fitness of Australian junior basketball is accurate (Study 1, Chapter 3). Such a study would also establish reference values for magnitudes and directions in changes in and between seasons of fitness and anthropometric characteristics within individual junior basketball players (Study 2, Chapter 4).

Table 2.1 - Anthropometry and physical fitness test scores

Mean values (SD) of physical tests results of male and female Australian junior basketball players collected between 1993 and 1996 with an age range of 14-17 y [284] compared to a 16-year-old urban New South Wales (NSW) school population [51].

	Height (cm)	Body mass (kg)	∑7 skinfolds* (mm)	CMVJ# height (cm)	20-m sprint time (s)	20-m shuttle Run (levels)
Female basketball	178.4 (9.6) N=139	69.2 (8.3) N=139	91.7 (18.9) N=362	46.5 (5.6) N=212	3.4 (0.16) N=99	10.5 (1.3) N=126
Male basketball	198.4 (7.7) N=95	94.4 (11.5) N=95	72.0 (27.0) N=261	65.5 (7.1) N=86	3.04 (0.1) N=84	12.0 (1.4) N=86
Female NSW school	164.9 N=423	57.2 421	not assessed+	not assessed	not assessed	5.4 N=399
Male NSW school	174.2 N=519	62.2 N=519	not assessed+	not assessed	not assessed	8.8 N=502

*∑7 = triceps, subscapular, biceps, supraspinale, abdominal, thigh, medial calf
#CMVJ - Countermovement Vertical Jump
+ in the NSW Schools Report, only sum of 3 skinfolds was reported

2.2.3 Normal Variations and Changes in Physical Tests

Many differences in physical test results (i.e. fitness and body size) between the genders and ages are related to biological changes associated with the adolescent growth spurt. Males after adolescence are typically taller and heavier [201] than females, have between 5-20% higher relative $\dot{V}O_{2max}$ [38], and score at least one standard deviation greater on most tests of strength and power, such as sprinting and grip strength [38]. Gender differences are partly explained by the natural variation in biological maturation between adolescent males and females. Males typically have a longer prepuberal growth period with greater velocity curves of peak height and body mass (Figure 2.1 and 2.2) stimulated by hormonal differences [258]. Substantial physical differences between older and younger individuals are evident during adolescent growth periods with both males and females showing sharp increases in body size and fitness during adolescence [258]. The smaller rate of increase in height with age of females compared with males is not surprising since females have a shorter growth period. Females tend to reach their peak height velocity at approximately 12 y and a height plateau by 15 y, whereas males peak at 14 y and still have not reached a growth plateau by 18 y [256] (Figure 2.1 and 2.2). These differences between genders and ages occur regardless of athletic training and have been well studied in the general populations [186]. There are significant implications in studying differences in athletic populations to assist coaches of age-group players tailor different style practices to different genders and ages of athletes.

Figure 2.1 – Adolescent changes in body mass

Typical body mass changes of males and females through adolescence. Based on data from Kuczmarski, et al. (2002) [186].

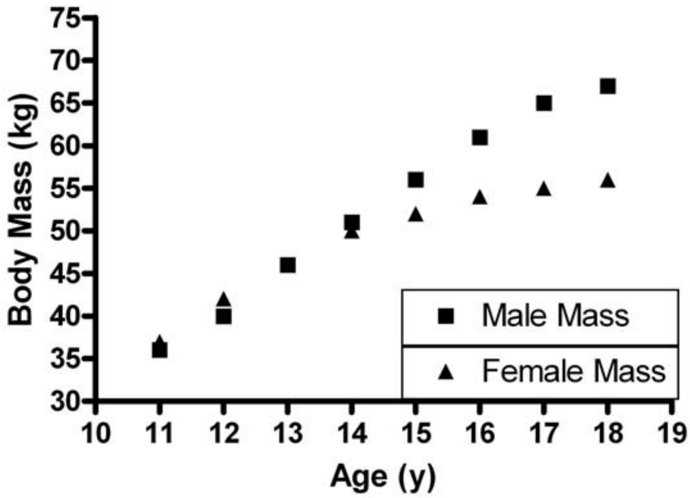
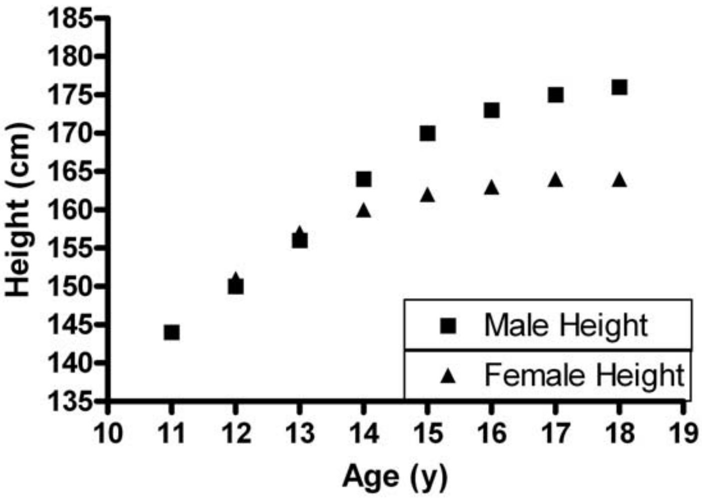


Figure 2.2 – Adolescent changes in height

Typical height changes of males and females through adolescence. Based on data from Kuczmarski, et al. (2002) [186].



2.2.4 Changes in Physical Fitness Over a Calender Year

In order to develop the various components of fitness in athletes, coaches typically periodise their training programs. A periodised approach involves an initial emphasis on high volume and low intensity training, before a gradual reduction in volume and increase in intensity over a period of several weeks to months [100, 307]. While periodised programs lead to greater fitness improvements in the experimental environment [250], there appears to be less consistent observations on fitness benefits of the traditional periodised training program in the typical training environment [176] (Table 2.2). Tavino *et al.* [293] tracked the progress of nine National Collegiate Athletic Association (NCAA) basketball players from the beginning of the pre-season to the post-season. They found that after 5 weeks of pre-season training players substantially decreased their body fat by 26% as measured by densitometry, and increased their anaerobic power by 13% as measured by the Anaerobic Power Step Test. Body fat levels then increased by 17% during the competition season with no accompanying changes in body mass or $\dot{V}O_{2max}$. Bolonchuk *et al.* [47] found no change in body mass or sum of seven skinfolds, but an improvement in $\dot{V}O_{2max}$ in eight NCAA players. Groves and Gayle *et al.* [113] tested eight university players four times over a year for body composition, vertical jump and Margaria-Kalamen Stair Climb power. They found that body fat decreased 20% over a year of training and body mass decreased 2.1% between the first and second tests before increasing 2.7% between the second and fourth tests. Caterisano *et al.* [62] found in 17 NCAA basketball players that body mass, body fat, and $\dot{V}O_{2max}$ did not change substantially over the course of a basketball season in starting players, while $\dot{V}O_{2max}$ declined by 10% in reserve players. Hoffman *et al.* [141] also studied 9 NCAA players and reported no significant changes in body fat, body mass, or aerobic conditioning (2.4

km run time) after 5, 15 and 25 weeks. Only showing significant decrements at week 15 were 27-metre sprint (-2%) and vertical jump height (-9%). Hunter *et al.* [151] tracked fitness progress over 4 years in 42 NCAA players. While they found some increase in body mass and vertical jump (9% and 8%, respectively), there were no substantial changes in $\dot{V}O_{2max}$ or body fat. Changes in strength measures such as the bench press range from showing no significant change [141] to improving by 7.5% [62] to 24% [151]. There does not appear to have been any attempt to explain the variety of findings or the ineffectiveness of some training programs designed to elicit changes in fitness.

One possible explanation for these studies showing limited change in fitness over the season is that they have based their analysis on statistical significance. It is clear that individuals respond to training programs with different magnitudes of change [278], so individual variation or responses should be reported as well as mean effects. Moreover the precision of the mean change using confidence limits should be reported, and effect sizes shown with probability that the true effect is meaningful in clinical (practical) terms rather than strict statistical significance alone [146, 148, 196, 235]. This approach is also underpinned by the notion that some investigators [150] inappropriately discard some effects reported as non-significant (e.g. p=0.07 or 0.15) that may actually be worthwhile in practical sporting terms [146, 148]. Finally, there appears to be no study of basketball fitness that also reports the reliability of the anthropometric, fitness or strength tests employed. Therefore, these topics were investigated in this thesis.

Table 2.2 – Fitness changes in a periodised program

Longitudinal fitness and anthropometric changes in American collegiate basketball players over different time periods

Reference	Time period	Sample	Fitness Characteristic	Change
Tavino et al. [293]	Pre-season#	9 NCAA males	Anaerobic Power Step Test	13% increase
	Pre-season#		Body Fat	26% decrease
	In-season+		Body Fat	17% increase
	Competition year*		$\dot{V}O_{2max}$ (treadmill running)	No change
	Competition year*		Body Mass	No change
Hoffman et al. [141]	15 weeks of pre-season#	9 NCAA males	27-m sprint time	2% slower
	15 weeks of pre-season#		Vertical jump height	9% down
	Competition year*		Body fat (skinfold)	No change
	Competition year*		Body Mass	No change
	Competition year*		Endurance (2.4 km track run time)	No change
	Competition year*		Bench Press	No change
Groves and Gayle [113]	In-season+	8 NCAA males	Body Mass	2.7% increase
	Competition year*		Body Fat	20% decrease
	Competition year*		Sargent Vertical Jump	No change
	Competition year*		Margaria-Kalamen Stair climb	No change
Bolonchuk et al. [47]	Competition year*	8 NCAA males	Body Mass	No change
			Body fat (skinfolds)	No change
			$\dot{V}O_{2max}$ (treadmill running)	increase

Caterisano et al. [62]	Competition year*	17 NCAA males	Body Mass	No change
			Body Fat (skinfolds)	No change
			Bench press	7.5% decrease for starters[1], 12% in bench players[2]
			$\dot{V}O_{2max}$ (treadmill running)	No change for starters[1], 10% decrease in bench players[2]
Hunter et al. [151]	Competition year*	42 NCAA males	$\dot{V}O_{2max}$ (treadmill running)	No change
			Body Fat (hydrostatic weighing)	No change
			Body Mass	Increase 9%
			Bench press	Increase 24%
			Sargent Vertical Jump	Increase 8%

*Competition year indicates the time from the beginning of the pre-season to the end of the competition season
+In-season indicates the period of time from the end of pre-season training to the end of the competition season
#Pre-season indicates the period of time from the beginning of annual training to the start of competition
[1]Starters refers to players that the first to play at the start of the game. The players are typically the players the coach has determined will have the greatest impact on the game.
[2]Bench players refers to team members put into the game to substitute starters.

Most field tests for basketball players have methodological variation inherent in the set up and measurement of the physical performance that does not represent biological change in the athlete [147]. Reported values in laboratory and field testing should account for this typical error of the measurement in both clinical and research settings [144]. An under-utilised approach emerging in the sport science literature establishes the threshold for practical significance as Cohen's small effect size [68, 146, 148, 196, 235]. The threshold or smallest worthwhile (practical) change is established as 0.20 of the test's between-athlete standard deviation. This method of evaluating the smallest worthwhile change or difference in test scores provides an objective means of confidently assessing the magnitude of observed effects in changes from test to test for a given individual or in differences between groups [147]. For example, Hunter [150] demonstrated a 1.2% drop in body fat in NCAA players tested once in October (11.0% body fat) and again in May (9.8% body fat) of the following year. This translates to a mean reduction of 10.4% (SD ±2.7) in body fat with an associated p-value of 0.07. While Hunter assessed this result as statically non-significant, there is still an 85% probability that the results of the training had a positive effect on body fat, despite the p-value being greater than 0.05, since the smallest worthwhile change is 0.54% (i.e. 0.2 × 2.7) compared to a mean estimated change of 1.2%. A similar case could be made for the 2.5 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$ improvement in $\dot{V}O_{2max}$ in the same study. While the reported p-value was 0.15, the smallest worthwhile change was 1.22 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$ based on a combined team SD of 6.1, as calculated from the average of the 'pre' SD (8.5) and the 'post' SD (3.6) equaling 6.1, then multiplying that by 0.2 (a 'small Cohen effect size) to equal 1.22 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$. Assuming 12 players were on the team, there is still greater than a 75% likelihood that the 2.5 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$ change was meaningful. Expressed with stringent 95% confidence limits, the range of the 'true' change lies between -1.04 and 6.04 $ml^{-1}\cdot kg^{-1}\cdot min^{-1}$, thus likely representing a meaningful and positive change in $\dot{V}O_{2max}$. There are obvious limitations in reporting only statistical significance without considering the practical implications of results.

2.2.5 Concern About Fitness By Coaches

Since the year 2000, Fédération Internationale de Basketball (FIBA) rule changes are pressuring players to move the ball down court and shoot more quickly. For example, there has been a reduction of the 30 s shot clock rule to 24 s, and the backcourt rule from 10 s to 8 s. Therefore, coaches are under pressure to ensure all players are fitter despite the declining levels of fitness in the general population in many Western nations [298]. This scenario has created a concern that coaches are being forced to recruit fitter players, but due to the decline of the general population, the fitness levels of younger players recruited to school and representative-level junior programs are also declining. There has been no apparent exploration of how declining fitness trends in the general population affect the fitness trends of adolescents recruited into high-level basketball programs. Anecdotal reports from leading coaches and basketball authorities suggest a trend of declining fitness in high-level junior Basketball Australia programs over recent years (Landon, L. General Manager, National Teams & Competitions, Basketball Australia, personal communication). Of particular interest are the secular trends of anthropometric and fitness test scores in the recruitment of new players to high-level basketball programs. There is a clear need to identify whether the coaches concerns about declining fitness are justified, and if they are, to develop innovative and effective methods for improving physical characteristics important to basketball.

A related issue is the need to identify the magnitudes of improvements in physical characteristics for players making the transition from junior to senior levels of basketball. A detailed analysis of physical testing results, entailing both fitness and anthropometric measures of different levels and genders, would allow individual players to gauge their strengths and weaknesses relative to a large number of other players [246]. Analysis of physical test score trends over several calendar years could also be used to evaluate a program’s recruitment patterns to assess if players of different sizes and fitness strengths should be targeted. A well developed and implemented physical testing program could prove to be a useful talent identification tool [134]. Therefore, the first study of this thesis will investigate the magnitude of differences and variability in body size and fitness test scores between Australian males and females of different levels of competition, and determine whether these scores have been changing in newly recruited players in recent years (Study 1, Chapter 3). The second study of this thesis will then investigate changes in body size and fitness tests within individual players at different levels of competition over a competitive season and over multiple years of basketball training (Study 2, Chapter 4).

2.2.6 Resistance Training to Improve Fitness

Resistance training, weight training, and progressive resistance exercise are just a few terms used interchangeably to describe using resisted movements to increase muscle mass, strength, or power. Basketball players are often prescribed a resistance training program in the latter years of their junior career, during the transition to senior programs, and in their senior, national, professional and/or international programs. Both male and female players now generally undertake extensive resistance training programs under the direction of their team coach or specialist strength and conditioning coach [243, 275] for a variety of reasons including injury prevention and improving power output. A report on American male and female high school athletes showed that of the 261 athletes participating, the rate of sporting injuries was 26% with an average rehabilitation time of 2.0 days for those athletes using weight training, compared to an injury rate of 72% with an average rehabilitation time of 4.8 days for those not undertaking weight training [130].

Resistance training has been shown to improve the lactate threshold [202], peak and average cycling power [253], total cycle work over 15 five-second efforts [253], and enhance high intensity exercise endurance such as isometric grip endurance [276], long-term cycling to exhaustion [132, 202], short term cycling and running to exhaustion [132], and sprint cycling performance [253]. Resistance training has improved the anaerobic threshold in cross-country skiers [136]. Resistance training can also improve a wide range of sports and sporting activities including throwing [75, 83], distance running time [217], cycling [253], sprint running [45], kayak starts [196], and jumping [19] as well as a variety of laboratory based tests (literature summarised in Tables 2.3, 2.4, and 2.5). Research investigating resistance training methods typically lack standardised training protocols so often training will involve methods such as low resistance circuit training [202], while training intervention research investigating well trained athletes often involve small study number so experimental control groups are occasionally absent [132]. Bishop and Jenkins [43] included a control group and found no substantial improvements in power, time to exhaustion, or VO_{2max} in the resistance trained group, the groups contained only eight subjects each. However, based on having eight subjects in two groups, the observed power to detect even moderate differences between groups was only 15%, so there seems a high potential that the non-significant result was in fact a Type II error. While improving such sporting skills may not appear directly relevant to basketball players, these data illustrate the capacity to improve important basketball fitness components such as peak power output, acceleration, anaerobic threshold, and repeat sprint ability. With documented improvements in a broad range of athletic capacities, it would seem logical to conclude that resistance training could be effective in assisting junior basketball players in improving upon the perceived fitness challenges they are facing.

The key issue for the players and coaches is how to maximise the effectiveness of the resistance training program as part of the overall annual periodised training program for high level basketball.

Table 2.3 - The use of resistance training in improving performance in court sport related tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[75]	Cronin et al., 2001	21 female netball players (17.2 ±0.9 y)	sport specific movements + bench press training at either 80% or 60% 1RM	Netball throw velocity	both groups increased ball throw velocity (1.1 v 1.3 m/s; ~10%) with no difference between groups
				bench press strength	strength group was significantly better (4.6 v 18.2%)
				bench press throw power	strength group was significantly better (2.7 v 13.3 W)
[116]	Häkkinen, 1993	10 elite Finnish female basketball players	22 weeks of the competitive season, 1-2 sessions per week of 30-80% of 1RM, 3-8 repetitions per set, 20-30 repetitions total, “performed with the highest possible velocity” + various plyometrics; no contrasting group existed	Squat jump height	improved 2.5 cm (12%)
				Counter-movement jump (height)	improved 1.4 cm (6%)
				maximal oxygen uptake	no change
				anthropometry characteristics	no change
				maximal isometric force of the leg extensor muscles	no change
				maximal anaerobic power output in an anaerobic jumping test	increased 6% during the first 15 s, and 7% over the total 30 s

Table 2.3 (continued) - The use of resistance training in improving performance in court sport related tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[142]	Hoffman et al., 1991	13 NCAA Division I male basketball players	in-season resistance training program, 1-2 sessions per week	1RM Bench press	unspecified significant improvement
				1RM Squat	no change
				27-m sprint	unspecified significant improvement
				Agility (T-test) run	no change
				vertical jump height	no change
[222]	Newton et al., 1999	16 NCAA Division I male volleyball players, 19 (+/- 2) y	8 weeks of either jump training (6 sets of 6 repetitions at 30%, 60% and 80% 1RM) or 3 sets of 6RM squat training	Squat jump height	increased 5.9% in the jump training group; no change in the strength training group
				three-step approach jump height	increased 6.3% improvement in the jump training group; no change in the strength training group
				components of jump power (e.g. power, force, velocity)	improved by between 3-19% in the jump training group; no change in the strength training group
				1RM Squat	no change in either group.

Table 2.4 - The use of resistance training in improving performance in sporting event related tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[44]	Blazevich and Jenkins, 2002	9 trained male sprinters (19.0±1.4y)	7 weeks of sprint training + squat training at maximal velocity exerted against either 30-50% 1RM or 70-80% 1RM	hip flexion isokinetic torque	improvement of 1.2% @ 1.05 rad·s^{-1}, and 11% @4.74 rad·s^{-1} with no differences between groups; 39.8% @ 8.42 rad·s-1 in the high velocity group was different to the -9.8% of the high resistance group.
				hip extension isokinetic torque	improvement of 15.5% @ 1.05 rad·s^{-1}, 10% @4.74 rad·s^{-1}, and 17% @ 8.42 rad·s^{-1}; no differences between groups
				20-m acceleration	improvement of 2%; no differences between groups
				20 m 'flying' running times	improvement of 3.5%; no differences between groups
				1-RM Squat	12% improvement; no differences between groups
[80]	Delecluse et al., 1995	63 recreationally active males (18-22 y)	2 times per week for 9 weeks: sprint training + either high velocity (plyometric) or high resistance (3 set of 6-15 @~10RM) training	total 100-m sprint time	high velocity training group improved 1.68%
				initial acceleration (0-10m)	high velocity training group improved a significantly greater 7% compared to high resistance training group 1% improvement

Table 2.4 (continued) - The use of resistance training in improving performance in sporting event related tests

Reference	**Author**	**Sample (age, sex, sample)**	**Training (movement, duration, intensity)**	**Test**	**Result**
[132]	Hickson et al., 1988	8 trained male and female cyclists and runners, 31 (+/- 1.2 y)	endurance training + strength training 3 days per week for 10 weeks @ 80% 1RM	leg strength	increased 30%
				short-term endurance (4-8 min)	improved ~12%
				cycling endurance	improved 20%
				anthropometry characteristics	no change
				muscle fibre area	no change
				fibre types	no change
				citrate synthase	no change
				$\dot{V}O_{2max}$	no change
[136]	Hoff et al., 1999	15 female cross-country skiers	training 3 days per week for 9 weeks: 3 sets of 6 repetitions @ 85%1RM; 7 subjects performed training at >60% 1RM for 3x20.	1RM	improved 15% only in the high intensity group
				peak force for 1RM	improved 36% only in the high intensity group
				time to peak force in double pole ski simulator	improved 27% only in the high intensity group
				power at $\dot{V}O_{2max}$	improved 26% only in the high intensity group
				$\dot{V}O_{2max}$	no change
				$\dot{V}O_{2Peak}$	no change
				Lactate concentration at $\dot{V}O_{2max}$	no change
				Time to exhaustion at maximal aerobic velocity	improved 137% in high intensity, 58% in low intensity

Table 2.4 (continued) - The use of resistance training in improving performance in sporting event related tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[159]	Johnston et al., 1997	12 trained female distance runners, aged 23-36 y	training either distance running only (32-46 km per week) or distance running + strength training (rep ranges of 6-20 across 14 different lifts)	VO_{2max}	no change
				anthropometry characteristics	no change
				running economy	improved 4% only in the resistance trained intensity group
				upper body strength	improved 24% only in the resistance trained intensity group
				lower body strength	improved 34% only in the resistance trained intensity group
[161]	Jones et al., 1999	40 NCAA Division I American football players	3-4 sets of 2-10 repetitions @ 65-95% 1RM bench press training at a conventional speed or attempting to move the resistance as rapidly as possible	seated medicine-ball throw	improvement was significantly greater in the maximal acceleration group (+0.69 m (10%) vs. +0.22 m (3%)
				1RM Bench Press	improvement was significantly greater in the maximal acceleration group (+9.85 kg (10%) vs. +5.00 kg (4%)
				force platform plyometric push-up	improvements ranged from 4-44% but were not different between groups

Table 2.4 (continued) - The use of resistance training in improving performance in sporting event related tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[196]	Liow and Hopkins, 2003	27 male and 11 female nationally competitive (New Zealand) sprint kayakers	groups trained 2 sessions per week for six weeks, 3-4 sets of sport specific lifts @ 80%1RM with either a 1.7 s concentric phase or a 0.85 s concentric phase	kayak time to distance: first 3.75-m	slow, 7.1%; explosive, 3.2%; control, 1.4%
				kayak time to distance: last 7.5-m	slow, 2.1%; explosive, 3.0%; control, 0.8%
				kayak time to distance: total 15-m	slow, 3.4%; explosive, 2.3%; control, -0.2%
[208]	McEvoy and Newton., 1998	18 (Australian) National-level baseball players, 24 y (+/- 4)	10-weeks of a ballistic resistance training program (30-50 percent 1-RM) or baseball-only	baseball throwing speed	increased 2% in training group; no change in non-resistance training group
				base running speed	increased 9% in training group; increased a statistically different 6% in non-resistance training group
[217]	Millet et al., 2002	15 elite (French) triathletes (~22 y)	14 weeks of either endurance only training (<70%VO_{2max}) or endurance + strength training (twice per week, 2-5 sets of >90% 1RM to failure on lower body)	VO_{2max}	no change
				velocity associated (VO_{2max})	improved 2.5% in the strength-training group only
				running economy over 3000 m	~12% better in the strength training group only
				mechanical power during maximal hopping	decreased 13% in endurance training group only
				maximal strength	improved ~20% in the strength trained group only

Table 2.5 - The use of resistance training in improving performance in laboratory-based tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[46]	Bobbert and Van Soest, 1994	mathematical model	high versus low strength	vertical jump height	increases with strength only with appropriate skills training
[120]	Häkkinen et al., 1985	11 recreationally strength-trained males (20-35 y)	three times per week 24 weeks squat training with intensities ranging variably between 70 and 120% (1-10 reps per set)	Squat strength	improved by 30%
				Unweighted squat jump height, power, and force	improved by 7%, 0%, and 0%
				40kg squat jump height, power, and force	improved 18%, 12%, and 10%
				100kg squat jump height, power, and force	improved 27%, 35%, and 65%
[119]	Häkkinen et al., 1986	21 recreationally trained males (20-35 y)	three times per week 24 weeks squat training with intensities ranging variably between 70 and 120% (1-10 reps per set) versus explosive resistance and plyometric training	iEMG	increased 22% in strength group; no change in velocity group
				isometric knee extension force	14% improvement in strength group; no change in velocity group
				isometric knee extension time to reach 30% maximal isometric voluntary contraction	decreased by 11% in the velocity group; no change in strength group

Table 2.5 (continued) - The use of resistance training in improving performance in laboratory-based tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[184]	Kraemer et al., 1995	9 members of the US Army	Upper and lower body resistance training, 3-5 sets @ 5-10 RM, 4 days per week for 12 weeks	1RM	increased 20-30%
				Wingate peak and mean power	improved 10-20%
				Type IIa fibres	increased from 23% to 41%
				Type IIb fibres	decreased from 19% to 2%
				Muscle cross-sectional area of IIa fibres	increased 24%
[202]	Marcinik et al., 1991	18 untrained males (25-34 y)	12 weeks of whole body strength training @ between 8-20RM for 1 set, versus non-weight training control	treadmill VO_{2max} or cycle VO_{2peak}	no change
				time to exhaustion	increased 33%
				lactate concentration at absolute workload	decreased ~30%
				lactate threshold	improved by 12%
				isokinetic peak torque, knee extension	improved by 31%
				isokinetic peak torque, knee flexion	improved by 35%
				1RM of different lifts	improved 20-50%

Table 2.5 (continued) - The use of resistance training in improving performance in laboratory-based tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[220]	Moss et al., 1997	30 recreationally trained physical education students	elbow flexion training 3-5 sets 3 times per week with a load of either 90% (2 reps), 35% (7 reps), or 15% (10 reps) of 1RM for 9 weeks	1RM	increased 15% in high intensity, 10% in moderate intensity, and 6% in low intensity
				power output at loads of 20-95%1RM	increased with moderate intensity by 10-40 W; increased with high intensity by 20-35 W
				cross-sectional area	increased 2.8% in moderate-intensity only
				correlation between 1RM and maximal power	0.93 with all groups combine
[253]	Robinson et al., 1995	33 moderately resistance trained collage males (20.4 +/- 3.5 y)	5 weeks of training 4 days per week (2 day split), 3-5 sets @40-75% 1RM resting either 180 s, 90 s, or 30 s between sets	strength	Long rest improved to a greater extent (7%) than short rest (2%)
				vertical jump height	no change in either group.
				15-s sprint cycle power and work	improved 3-12% with no difference between groups

Table 2.5 (continued) - The use of resistance training in improving performance in laboratory-based tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[279]	Sleivert et al., 1995	32 untrained males (18-28 y)	14 weeks of either sprint training (3 times per week) or strength-sprint groups (1-3 days per week, 3 sets of 8-12 reps@10RM + sprint training)	Fibre hypertrophy	increased in all training groups equally (10-16%)
				10RM	both strength training groups improved >40%
				15 s cycle ergometer power	increased in all training groups (7-11%)
				isometric strength	no change
				isokinetic strength	no change
				rate of torque development	no change
				tibial nerve conduction velocity	improved 2-4%; no difference between groups
				iEMG	no change

Table 2.5 (continued) - The use of resistance training in improving performance in laboratory-based tests

Reference	Author	Sample (age, sex, sample)	Training (movement, duration, intensity)	Test	Result
[317]	Wilson et al., 1993	55 recreationally resistance training males	10 weeks of either heavy squat lifts (3-6 sets of 6-10RM), plyometric training (depth jumps), or weighted squat jumps (>30% 1RM)	30-m sprint	improved ~1% in max power group
				jump (counter movement and squat) power	improvement made by the power training group (~15%) were greater than the strength training group (~6%) and by the plyometric training group (~8%)
				power output in a maximal cycle test	maximal power improved ~5%; strength group improved 1.8%
				maximal isometric force	improved 14% in the strength training group
				maximal isometric rate of force development	no change in any group
				force in the isokinetic leg extension (2.53 rads/s)	improved 7% only in the maximal power group

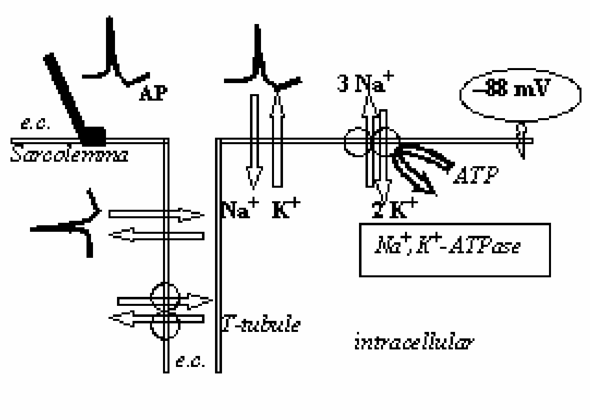
2.3 Fatigue And Failure In Resistance Training

2.3.1 Overview of muscle contraction

Conventional resistance training involves dynamic, voluntary activation of specific muscle groups against a resistance. Voluntary activation of a muscle group involves a complex interaction of events. Signals for voluntary contractions originate in the motor cortex and travel through descending spinal pathways to stimulate the muscle to contract. These signals travel as an action potential (AP) that is relayed by a series of depolarisation-repolarization cycles through neural and then muscle tissues. An action potential initially involves the opening of Na^+ channels that allow Na^+ movement into the cytoplasm as a function the electrical and concentration gradients. These events cause depolarization of the membrane from its initial charge of approximately -88 mV. Sodium channels are then inactivated while potassium channels are activated. Moving down the electrical and concentration gradients, potassium moves out of the cell, thereby causing repolarization of the cell. In order to maintain the membrane gradients of Na^+ and K^+ that account for the polarity differences, the cell relies on the Na^+, K^+ pump to return Na^+ and K^+ back to their original concentrations on either side of the membrane [67, 210, 225] (Figure 2.3).

Figure 2.3 – Action Potential

Propagation of the action potential occurs along the sarcolemma and into the t-tubule by movement of Na^+ and K^+ across the sarcolemma. Illustration from McKenna [210]



Excitation-contraction coupling refers to the sequence of events by which excitation of the muscle membrane leads to increasing force resulting from cross-bridge cycling activity within the muscle fibre. Dihydropyridine receptors detect the voltage change of the action potential in the t-tubular membrane that triggers the release of Ca^{2+} from the sarcoplasmic reticulum via ryanodine receptors [187]. As the calcium concentration rises within the sarcoplasm, the events of the Sliding Filament Theory unfold.

Prior to excitation, the head of the myosin myofilament does not directly interact with G actin molecules of the actin myofilament. For the myosin to be in this ready position, it must have had an ATP molecule attach to its ATP binding site and the ATP must be hydrolysed by myosin-ATPase. This ATP hydrolysis forms ADP and Pi and the energy released is stored in the head of the myosin. When released from the sarcoplasmic reticulum, Ca^{2+} binds to troponin (Tn) –C of the actin myofilament, causing a conformational change in tropomyosin. These events culminate in the movement of Tn-I that covers the active binding site. With the active binding site now exposed, the myosin head binds to the actin, forming a cross-bridge between the two filaments. The attachment of the energised myosin to actin releases the stored energy and the myosin head shifts its orientation, pulling the actin filament toward the centre of the sarcomere. At the end of this power stroke, ATP attaches to the ATP binding site of the myosin head and is hydrolysed, thus returning the myosin head to its ready position. This cycle of events continues as long as calcium remains present at a sufficient concentration in the cytosol. Relaxation of the muscle occurs when cytosolic calcium concentration is lowered by an increased activity of the sarcoplasmic reticulum Ca^{2+}-pump, which actively pumps calcium back into the sarcoplasmic reticulum [188].

Afferent nerves carry sensory stimuli about the contraction, such as muscle stretch and movement velocity, back to the brain (primarily the cerebellum) by way of the dorsal and lateral columns of the spinal cord to adjust properties of the contraction [57]. For example, if greater force is required additional motor units are recruited (increasing recruitment) or the active motor units receive increased frequency of stimulation (increasing rate coding). As contractions continue, fatigue develops and force declines [97]. A number of authors have previously reviewed the variety of neural [33, 82, 107], metabolic [262], and ionic [112] mechanisms that purportedly elicit a decline in force (i.e. fatigue) [97] and eventually task failure [152]. Identifying mechanisms of fatigue or even the broad category of fatigue (i.e. central or peripheral) is difficult because mechanisms will vary depending on the intensity, duration, and muscle group, and type of contraction [30, 33].

2.3.2 Neural Inhibition

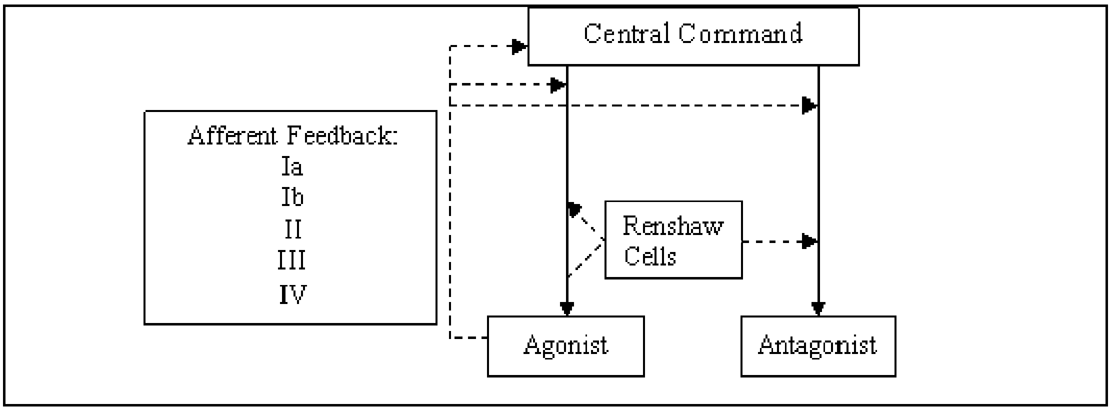
Fatigue can be defined as a “reduction in muscle power output during exercise, which is reversible during recovery” [210], occurring centrally (from the brain to the neuromuscular junction) and / or peripherally (after the neuromuscular junction) [40]. So-called “central fatigue” can arise from a reduction in voluntary activation as a result of reduced motocortical and corticospinal activity (“central command”), or decreased propagation of the action potential along the motor neurons, and/or the motor nerve [40, 107]. Such reductions reflect muscle afferents feeding sensory information from the muscle back to central command and directly onto the motor neurons, thereby altering excitability of the motor neurons (Figure 2.4). Such central fatigue can be responsible for decreases in force of up to 50% of maximal isometric voluntary contractions [103] and 20% of maximal dynamic contractions [156].

As fatigue progresses after repeated voluntary contractions, or when a subject attempts to lift a load that exceeds the maximal voluntary force they can exert, there are several central (neural) mechanisms that inhibit muscle activation. These mechanisms also stabilise the joint to protect the muscle and joint from mechanical or metabolic injury [171, 210] (Figure 2.4). The firing frequency of the motoneuron stimulates Renshaw cells, interneurons that receive input from descending motor pathways to inhibit the active motoneurons, a process referred to as *recurrent inhibition*. Golgi tendon organs (Ib afferents) and Group III and IV afferent nerves sensitive to mechanical (e.g. high tension, stretch), biochemical (e.g. elevated potassium, hypoxia), and thermal stress [107] establish a negative feedback loop. This loop inhibits activation of agonist muscle groups [167, 257], a process referred to as *autogenic inhibition*. These inhibition signals to the agonist and synergistic muscle groups decrease the muscle firing rate during fatigue [42, 108] (Figure 2.4).

Renshaw cells and Golgi tendon organs will also increase activation of antagonist muscle groups by inhibiting inhibitory interneurons that synapse with the antagonist muscle (Figure 2.4). This process is referred to as *coactivation*, which Pesk and Cafarelli found increased by 60% during fatiguing contractions [245]. Coactivation is a characteristic necessary to stabilise joints, but acts to resist force generation through activation of antagonistic muscle groups and may decrease net force exerted by up to 11% [26, 245]. These inhibitory signals culminate in a decline in voluntary force generation of a muscle.

Figure 2.4 – Neuromuscular feedback mechanisms

Schematic of the interaction of afferent (sensory) neurons and interneurons responsible for excitation of agonist and antagonist motoneurons. In response to fatigue, agonist sensory feedback (afferents) leads to autogenic inhibition via peripheral and central command. High rates of stimulation will also stimulate the agonist inhibitory interneuron (Renshaw cells) to cause recurrent inhibition. Central and peripheral mechanisms and Renshaw cells also stimulate coactivation of antagonists. All serve to reduce force of the agonist and increase force of the antagonist, thereby protecting the muscle and joint from injury. Based on Gandevia [107] and Enoka [97].

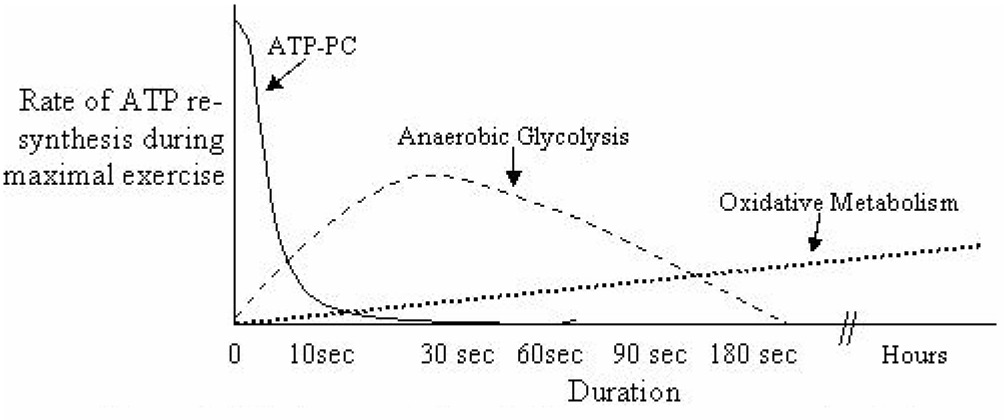


2.3.3 Metabolic Fatigue and Lactate

Mechanisms of energy supply during intense activity, primarily creatine phosphate hydrolysis and glycolysis, have been reviewed in detail previously, and will not be repeated in detail here [262]. However a brief review is required to designate specific issues relating to resistance training and task failure. Fundamentally, cross-bridge cycling is hindered when ATP demand exceeds ATP resynthesis, resulting in a broad range of intracellular signalling mechanisms that begin to impair contraction [227, 248]. Typically, resistance training sets are of short duration (~20-40 s) but of high intensity, relative to aerobic endurance programs of longer duration (>20 min). Therefore, the major initial source of ATP for resistance training comes from ATP stored intramuscularly, while the major sources of ATP resynthesis are anaerobic creatine phosphate (CP) hydrolysis and glycolysis [115]. As the activity increases in duration, ATP-resynthesis becomes increasingly dependent on oxidative metabolism (Figure 2.5) [205]. While aerobic metabolism plays a role in the long term recovery of ATP stores during recovery, the dominant source of ATP resynthesis during resistance training is stored ATP, CP, and glycolysis.

Figure 2.5 – ATP resynthesis

Relative energy contribution of different energy systems for ATP resynthesis during exercise of different durations. Adapted from Bompa [49].



Muscular contraction is fuelled by energy released from hydrolysis of stored ATP. To prevent rapid depletion of ATP, CP serves to rapidly resynthesise ATP via the creatine kinase reaction. Gaitanos et al. demonstrated that muscle CP content decreased by 57% and ATP decreased by 13% over the course of a six second sprint [106]. This rate of decline is not linear, and slows for longer activities as decrements were only 70% and 40% respectively after a 30 s sprint [63]. While CP is a small contributor of energy to activities such as biceps curls, accounting for ~16% of the required energy [189], depletion of CP after exhaustive exercise can be extensive [260, 261, 295]. Restoration of CP between sets can be rapid, recovering 50% in 30 s, but takes 2-5 minutes to recover fully depending on cellular pH and muscle oxidative potential [129, 198, 215, 260, 295]. Incomplete restoration of CP, and thus the inability to rapidly resynthesise ATP, has been linked to fatigue during resistance training, as CP recovers less with each successive set as a function of insufficient time between sets [295]. Therefore, fatigue may be partially linked to depletion of CP [126].

Glycolysis has also been proposed as a rate limiting process in exercise. The association between high intensity exercise, an increase in muscular lactate concentration, as usually measured by blood lactate concentration [5, 178, 183, 295] and a corresponding exercise-induced decline in pH [198, 214, 215], underpins the assertion that acidosis is a primary source of fatigue [252]. One proposed mechanism is that the lactic acid produced during glycolysis inhibits phosphofructokinase and phosphorylase thereby impairing anaerobic glycolytic ATP resynthesis [260, 290]. A second mechanism is the inhibition of the calcium/troponin interaction during cross bridge cycling [213, 314]. Despite the widespread popular acceptance that accumulating lactic acid results in fatigue, many investigators now dispute the assertion that declining pH is a primary contributor to fatigue [53, 198, 230, 244, 308, 316]. There is debate particularly over the role of lactic acid in muscle fatigue [52, 98, 226, 313], and some researchers even challenge the existence of lactic acidosis [252]. Nielsen *et al*. [226] found that lactic acid, in addition to other acids, actually had a force sustaining effect in isolated rat muscle, suggesting that acid has a protective rather than a limiting function. Westerblad *et al*. [316] found that acidifying mouse muscle with CO_2 only effected force output at temperatures well below physiological temperatures (e.g. 12ºC), but found that as temperature increased the effect on force was less until it eventually became non-significant at 32ºC. Therefore, current evidence suggests that declining pH plays a much smaller contributing role to muscular fatigue, if any at all, than previously thought. Other reviews provide more detail on accumulation of phosphate [313] and potassium [248] rather than lactate or pH disturbances [52] as primary causes of muscular fatigue. While these studies have investigated the role of lactic acid and declining pH in directly impairing force production, they have not investigated other indirect causes of fatigue, such as declining metabolic enzyme rate or release of calcium from the sarcoplasmic reticulum.

2.3.4 Other By-products and Sources of Ionic Imbalance

Under high levels of energy demand, the processes that stimulate a motor unit (generation of the action potential), store energy within the ATP molecule (ADP phosphorylation), and release stored energy for work (hydrolysis), generate other metabolic by-products besides lactate and H^+ that function as intracellular signals to stimulate fatigue. The exact mechanisms by which these by-products induce fatigue remain unclear and are the source of great debate. By-products associated with fatigue include ADP [262], elevated extracellular potassium [103, 104, 248], and inorganic phosphate [214, 226, 248, 313]. Accumulating by-products may reduce the rate of metabolic enzymes such as creatine kinase [129] or stimulate chemically sensitive group IV afferents that inhibit the spinal motoneuron [16, 167, 174, 257]. Accumulation of Pi during fatigue causes Ca^{2+}-Pi precipitation within the sarcoplasmic reticulum, thereby reducing the Ca^{2+} available for release from the SR [12] and also impairs cross bridge cycling [69, 315]. Conformational changes in ryanodine receptors [195] and reductions in energy substrates such as glycogen [286] are related to fatigue-induced reductions in calcium release. Elevated extracellular potassium is also associated with fatigue [103, 104, 248]. During intense activity there is an impairment of the Na^+, K^+ pump through depression of maximal Na^+, K^+ ATPase activity [103, 104]. There can be a doubling of intracellular sodium and a 20% decline in intracellular potassium during high levels of fatigue, thereby decreasing membrane excitability due to potassium loss [277]. These events elicit a 15-25% decrease in the amplitude of the compound muscle action potential during low and moderate intensity fatigue [33, 103]. The impairment of the Na^+, K^+ pump has been implicated as a fatigue mechanism either through prolonged disruption of membrane potential [104] or accumulating extracellular K^+ acting as a communication mechanism to further slow ATP production [248].

2.3.5 Muscular Failure

Under many resistance training designs, the terms *task failure* [152] or *muscular failure* [189, 288] are used to describe the point at which the athlete cannot move the given load further than a critical joint angle, referred to as the *sticking point* [95]. Some studies show substantial strength gains can be made by utilising training methods that involve high levels of fatigue, even if resistance is at relatively low intensity when a high number of repetitions are completed [28, 65, 81, 220], and that fatigue to the point of muscular failure can improve strength [81, 254]. Within the resistance-training community there is also anecdotal support for recruiting the assistance of a spotter after reaching muscular failure to perform further *forced repetitions* [50, 309]. The difficulty in assessing the potential applications of the existing free-weight resistance training studies is that they fail to control training variables such as volume (e.g. one set versus multiple sets) [185], duration of the training period (e.g. ~four min versus >20 min) [102], or training intensities (e.g. 60% versus 100% MVC) [165]. However these are critical training variables that determine or influence the outcome of the training program [182]. Studies only using untrained subjects [10, 249] performing single joint, isometric/isokinetic training [28, 31, 81, 102, 164, 165, 241, 254], are unlikely to relate directly to sporting applications. All of these issues leave the question of the value of training to the point of muscular failure and forced repetitions unanswered [288], particularly in team-sport athletes.

It seems intuitive that when two groups of athletes are each training at equal work volume at equal intensity that both groups would experience equal gains in strength [24] and hypertrophy [8]. However, Rooney *et al.* [254] showed using elbow flexion training that even when training volume (6-10 reps, 3 time per week for 6 weeks) and intensity (6RM) were equal, the group training continuously to failure had greater strength improvements than a second group training equally but employing 30 s rest between repetitions. While Rooney *et* al. were able to control the number of repetitions, there was no method of accounting for other training variables such as total time under tension, work performed, or power output. Additionally, Rooney *et al*. conducted their research on elbow flexion training, a movement that is rarely a limiting factor in athletic performance. Modification of the training protocol used by Rooney *et al*. could elicit repetition failure in training groups on multi-joint lifting techniques to elucidate the value of training programs prescribing forced repetitions. Better controlled research needs to be conducted before definitive conclusions can be drawn regarding the importance of training to repetition failure, though additional forced repetitions appear unnecessary for strength development. Therefore, this thesis will explore the methods of quantifying important training variables in multi-joint, free-weight resistance training programs that involve training to the point of muscular failure when important training variables are controlled (Studies 3 and 4, Chapters 5 and 6) and when multiple sets of forced repetitions are used (Study 5, Chapter 7).

2.4 Training Programs

Traditional resistance training programs are generally constructed on the same three set model of training that has existed for decades [37]. Contemporary programs manipulate the intensity, number of repetitions per set, number of sets, rest duration, and volume for optimal muscular strength development [236, 249]. Other programs manipulate these variables to develop optimal muscular power [44, 128] or hypertrophy [8, 133]. These variables have also been the subject of extensive reviews because manipulation of these variables can elicit training responses specific to the goals of the individual athlete [60, 182, 189]. A well designed, long-term resistance training program will involve undulating volume and intensity of training to develop different fitness goals (e.g. strength, power, hypertrophy, recovery, etc.) over a training year [49, 100, 251, 307].

Training programs designed to improve maximal strength traditionally employ three to four sets of six repetitions, at an intensity of at least 80% of a subject's maximum lift [249]. This approach assumes that high loads are necessary to improve strength, and that fatigue should be avoided as it lowers the amount of tension a muscle can exert [15, 102, 117, 122, 181, 203, 241, 269, 304, 311]. Athletes dependent on strength, such as powerlifters, will generally avoid "power" or "hypertrophy" programs because the training is typically performed with loads that are too low to develop maximal strength. The duration of sets and rest intervals have been proposed as important elements in development of strength as they are major determinants of fatigue. Consequently long rest periods are generally used to develop strength [102, 241, 253, 311]. Applications of this style of resistance training program are intended for dedicated strength athletes. A strategy of maximising slow velocity training for high velocity movements [31, 160] may well have substantial benefits for team sport athletes seeking both strength and power development.

Traditional hypertrophy training regimes typically involve high volumes of training of greater than 12 sets at 8-12 repetitions per set, using moderate loads (70-75% 1RM), at a slow velocity. Athletes focusing on hypertrophy will often avoid power and strength training, as the volume and fatigue of training are generally considered too low. Research investigating high repetition training has revealed that training at moderate resistance with a high number of repetitions had a greater detriment on evoked contractile properties of fatigued muscle than high-resistance/low-repetition training, indicating that high repetition fatigue affects contractile mechanisms more than neural properties in the muscle [30]. Utilising high volume training to elicit high fatigue training typical of hypertrophy training programs is likely related to the generation of higher levels of exercise-induced by-products [281]. Schott et al [270] proposed that exposure to metabolites such as phosphates and H^+ increases insulin-like growth factor 1 (IGF-1) to stimulate protein synthesis and ultimately strength adaptations, as supported by ischaemic training data [274]. The higher metabolic demands of fatiguing contractions on the fibre may also stimulate the maintenance of capillary density often seen in body builders that does not occur in strength athletes [206, 267]. The high forces generated by strength athletes may not be necessary for bodybuilders [8].

Power training in resistance training programs can be divided into three different categories: high-resistance low-velocity (>80% 1RM) [44, 160, 196], low-resistance high velocity (<30% 1RM) [166, 297], and maximal power training (30-50% 1RM) [208, 317]. Combination training that alternates high- and low-resistance sets to maximise both strength and power is also a useful method of training [20, 101, 128]. Since an athlete generates the greatest power in performance testing at the power predominantly trained at, a load of 30-50% moving at maximum velocity should maximise the stimulus for power [208, 317]. Higher intensity training is avoided since lower power output is produced using higher loads due to the slow velocity. Long rest periods with low volume are also typical of power training because less power can be generated when an athlete is fatigued [5]. Therefore, athletes that rely on speed for performance typically avoid high load strength and high volume hypertrophy programs common in resistance training, because such programs are often performed too slowly to enhance power.

Power training using high velocity on traditional resistance training equipment (e.g. barbells) may be inappropriate with many lifting techniques. Kinetic analysis has revealed that 40% of the lift using 45% of the subject's 1RM bench press is spent in a deceleration phase as the agonists and antagonists balance the necessary forces to protect the joint [205], thus training *de*celeration [224]. This deceleration decreases to 24% of the lift when an athlete is lifting 100% of their 1RM [95]. While the ideal approach should involve lifts where the end point loading is reduced to 4% [224, 317], ballistic lifts require specialised equipment such as a Smith Machine or Olympic lifting plates and platforms. Therefore, a potentially viable strategy for training power on traditional resistance training equipment involves the use of heavy loads while the person attempts to move at maximal velocity [160].

2.4.1 Resistance Training Adaptations and Benefits to Team Sport Athletes

2.4.1.1 Neural Adaptations

Failure of a muscle group to generate sufficient force to overcome an external force has several different aetiologies relating to neural activation. While strength capacity of an isolated muscle fibre is generally considered proportional to muscle cross-sectional area (CSA) the increase of strength during the initial weeks of a training program are not always directly proportional to muscle hypertrophy [29, 82, 119, 121, 123, 197, 218, 320]. Ploutz and colleagues reported a 14% increase in strength accompanied by only a 5% increase in CSA [242]. The term 'neural adaptations' is used to summarise these adaptations made by the nervous system in response to resistance training and have been extensively reviewed elsewhere [29, 61, 105, 263, 264]. Briefly, much of the initial rapid progress experienced by an individual new to strength training generally relates to adaptations within the motor cortex that improve the coordination of agonist and synergist muscle groups [66, 84]. Carolan and Cafarelli [58] found a 20% decrease in antagonist coactivation in the first week of a resistance training program, a process referred to as *reciprocal inhibition*, by way of enhancing stimulation of the Ia inhibitory interneuron. There is also a parallel reduction in the activity of Renshaw cells and Ib inhibitory interneuron which reduces the amount of inhibition to the agonists and synergists (i.e. reduced recurrent and autogenic inhibition) [2]. Therefore, two key benefits of resistance training are the capacity to reduce inhibition to agonists and synergists, and increasing inhibition to antagonists.

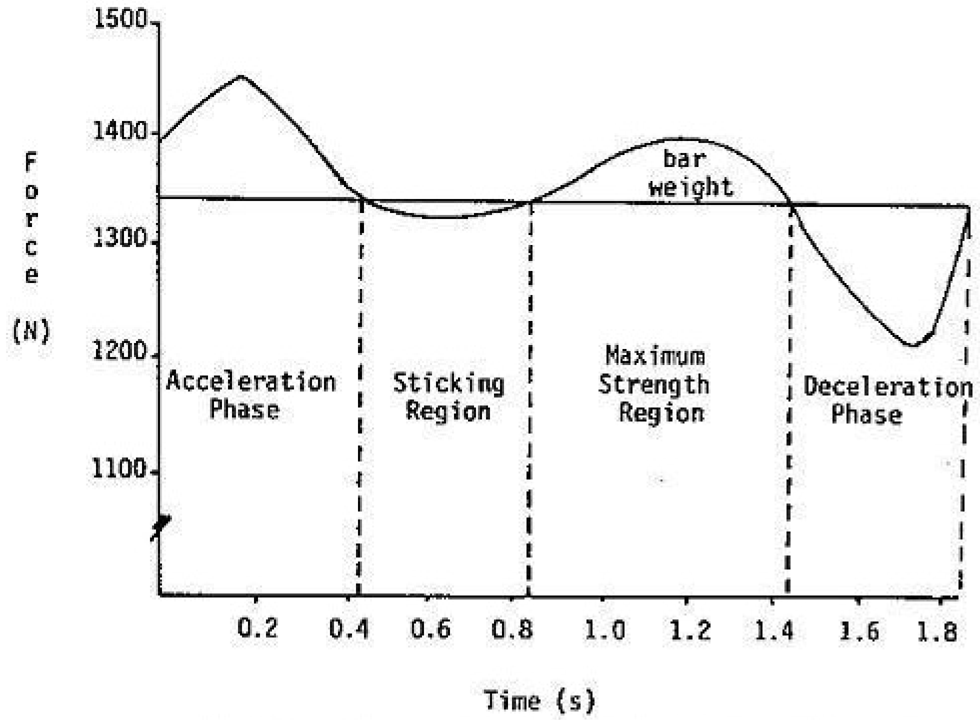
The traditional model of neural adaptations mainly describe their effects occurring in novice strength trained subjects [29] before stabilizing after an initial 6-8 weeks [29, 105, 263]. Häkkinen and colleagues demonstrated in experienced weightlifters that training blocks of several months of lower intensity training results in reduced iEMG during maximal voluntary contractions at the end of the training period, but periods of higher intensity training increased iEMG during maximal voluntary contractions [118, 122]. Judge et al. [163] also concluded neural adaptations were present from EMG analysis in experienced track and field athletes after 16 weeks of a sport-specific resistance training program. These findings suggest that adaptation of the nervous system continues even after many months of resistance training. By inducing neural responses, fatigue and high intensity training may strengthen the neural adaptations, even in trained athletes [118, 122, 163, 180].

Training to the point of repetition failure may stimulate several neural mechanisms for promoting greater strength development over and above those already present in non-failure training. Fatigue to the point of repetition failure has been indicated to maximize recruitment and the training stimulus to all muscle fibres [175, 239]. Pick and Becque [239] and Komi [175] indicated that the extent of activation is related to strength development. Pick and Becque [239] noted in individuals training one set to failure that each repetition increased the iEMG signal, and iEMG was highest between 80-100% of reps to failure. Pick and Becque [239] concluded that the final repetitions to failure were critical for the training response given their high activation potential. The importance of high intensity and fatigue is likely related to the *size principle*, which dictates an assigned order of motor unit activation with low threshold motor units initially activated for their higher precision and lower force endurance properties. Additional motor units of higher threshold are recruited as increased force or velocity is required [131] and fatigue increases [41, 92, 109, 254, 265]. Since activating and overloading a high number of motor units is important to facilitate strength development [281, 304], training to repetition failure should maximise the number of active motor units and therefore the magnitude of the adaptations made by these motor units[200, 254]. As a muscle approaches task failure more motor units are recruited but firing frequency begins to decline [59, 152]. Therefore, there is a potential for failure training to optimally develop strength by maximising motor unit recruitment. Therefore, fatigue from heavy lifting is necessary to stimulate high-threshold motor units not activated by lower intensity contractions. The capacity to activate and train high threshold motor units has particular relevance to team sport athletes who need to exert high levels of force, as it is these high threshold motor units that are capable of generating the highest amount of force and power. Since the highest threshold motor units are not activated until there is a high relative load or high levels of muscular fatigue, training with very high loads and fatigue should be useful in training the activation of these motor units.

An additional advantage in training to the point of repetition failure relates to the stretch-shortening cycle (SCC). Previous research [95, 224] has demonstrated four areas in the concentric phase of the bench press relating to increasing or decreasing power (Figure 2.6). During the concentric movement, the time-course of changes in power shows an initial spike before decreasing into a so-called "sticking point", after which the power begins increasing again to the repetition's peak power, before finally decreasing again to finish the concentric phase. While power production in the second (sticking point) phase would be dependent on voluntary activation of cross-bridge cycling of the active muscle groups, power production during the first phase involves both voluntary activation and the SCC given it is immediately preceded by the eccentric movement [96]. The SCC components are much more resilient against fatigue than voluntary contractions as SCC components involve reflex and elastic components [96]. Consequently, only when involuntary SCC components normally exerted during the first phase are no longer adequately compensating for the dramatic loss of power from voluntary cross-bridge cycling would there be insufficient power generated to push through the sticking point [95]. Since stretch reflexes are trainable [306], developing these components over a longer training period (e.g. 6-8 weeks) may be a key component to improving the ability to generate sufficient power to continue through the sticking point, and therefore perform additional repetitions.

Figure 2.6 – Four regions of the bench press

Graph from Elliot *et al.* [95] depicting four different phases of high and low force during the bench press concentric movement.



Neural adaptation also has a critical psychological component. Training to repetition failure may be beneficial in resistance training programs since exerting maximal efforts is a skill that must be learned; generating a maximal effort has high mental demands and training for full activation during resistance training is a mental skill required by athletes [154, 320]. An athlete well-practiced at exerting truly maximal efforts during resistance training may have a higher amount of supraspinal discharge [4]. In a classic study investigating regulation of muscle force, Ikai and Steinhaus found that muscle force could be maximized under a state of hypnosis, implicating the involvement of cognitive and mental skills in maximal efforts [154]. Should such a characteristic be trainable, athletes on resistance training programs theoretically could train at higher intensities or higher volumes and attain greater physiological and performance benefits.

2.4.1.2 Fibre Adaptations

Many neural adaptations occur in response to resistance training that effect neural inhibition and central activation, in addition to adaptations that occur within the muscle. Hypertrophy of muscle is one of the most popular reasons for individuals to begin a resistance-training program. The functional use of hypertrophy and body size in basketball and other athletic competitions is well understood in the general and sporting communities. Hypertrophy occurs when resistance training alters myosin heavy chain gene expression to increase the efficiency of mRNA translation into contractile protein to predominate over protein breakdown [312]. While a wide range of signalling pathways and regulatory molecules that stimulate specific gene expression have been proposed [125], the precise mechanisms remain unelucidated [48, 125, 203]. Increased muscle protein synthesis that occurs with exercise [64] is related to increased size of sarcomeres in parallel and series [110] or thickening of the myosin heavy chains [13, 94]. Hypertrophy-style training programs have resulted in 20-40% increase in muscle mass [180] but this has a high degree of heritability [153].

In the novice resistance trainer, protein synthesis begins within three hours of the training session, and exceeds the protein breakdown rate within 48 hours [39, 238]. However it can take many weeks for actual muscle hypertrophy to become visibly apparent [237, 285]. Unfortunately, hypertrophy can be slow to develop in athletes experienced in resistance training, taking many months to achieve substantial improvements [10, 118] and eventually plateaus [124]. As previously discussed, Behm et al. [30] indicated that high repetition training has a greater detriment on evoked contractile properties of fatigued muscle than high-resistance/low-repetition training. Since high fatigue models of training place greater stress on muscle fibres than neural innervation [30], they are more effective at promoting muscle hypertrophy [29].

The conversion of muscle fibre types from IIb fibres to IIa is another important resistance training adaptation [13] to team sport athletes as it allows higher volumes of work to be preformed at high intensity. Other terms are used to describe the type IIb 'intermediate' or 'transition' fibres (e.g. IIx) [282] but the most widely cited nomenclature is type IIb to indicate the fast-twitch glycolytic fibre capable of transition to IIa fast-twitch, oxidative fibres. The amount of contractile protein and type of fibres play important roles in a muscle's size, strength, and speed [153, 268]. Within the first two to four weeks of high fatigue resistance training, there is evidence of type IIb fibre conversion of myosin ATPase and heavy chains into that of type IIa [13, 180, 242, 285]. This conversion, in conjunction with the increase in muscle cross sectional area, allows the muscle to generate more force at a greater rate. Type IIa fibres have the advantage over IIb through greater endurance capacities [57], which has potential to provide further benefit to team sport athletes.

The substantial muscle fibre type remodelling in the early stages of a new resistance training program are correlated with the endocrine responses to exercise [285]. Resistance training stimulates a transient, acute increase in the concentration of both testosterone and growth hormone [177, 179, 285] that promote muscle cell production and growth by acting on the many genes which stimulate protein synthesis [10, 207]. Activity of the endocrine system is higher in higher fatigue modes of training [179]. These changes result in Type II muscle fibres of trained lifters being up to 45% larger than sedentary men [93]. These hormonal responses are one of the key mechanisms that regulate the adaptations to resistance training in highly trained athletes [180].

2.4.1.3 Metabolic

Fatigue and repetition failure can result when there is an imbalance between ATP hydrolysis and resynthesis. Resistance training can increase levels of stored ATP, creatine phosphate, free creatine concentrations, and glycogen [197] and the activity of glycolytic enzymes [294]. Each of these adaptations allows for a greater provision of ATP during high intensity exercise. Therefore, resistance training may benefit team sport athletes by improving energy storage and delivery capacity in addition to the improvements in size, strength and power.

While metabolic by-products induced by high volume training such as Pi, H^+, and K^+ play a role in fatigue, they may also indirectly benefit the physical preparation of team sport athletes [270]. Metabolites play a role in promoting increases in muscle mass [270, 274, 281]. Another possible, though not directly explored benefit of resistance training to team-sport athletes, is a possible increase in buffering capacity in skeletal muscle [273]. However, the mechanism for this adaptation is unclear given recent evidence against declining pH as a cause of fatigue. CP acts as a buffer in the reversible creatine kinase (CK) reaction during ATP resynthesis, thereby accounting for up to 38% of a muscle's buffering capacity [260]. Resistance training can improve storage capacity of CP [197] and activity of CK [296] confirming the effectiveness of high intensity training to improve buffering capacity, and potentially anaerobic endurance [253, 261]. Collectively these benefits justify the inclusion of resistance training in the fitness programs of a wide range of individual and team sport athletes. To date there has been no direct investigation of the effects of resistance training on buffering capacity.

2.4.2 Critique of Past Resistance Training Research for Sporting Applications

There have been many review articles examining resistance training methods [182], the effects of resistance training [34, 117, 219], or the effects of different resistance training programs on muscle strength [24], power [75] and hypertrophy [189]. Historically, there has been a belief among coaches that the slow contraction speeds typical of strength training programs result in slow execution of sport-specific skills [305]. This belief has been reinforced in research reviews [29, 219, 264] and is supported by empirical evidence describing the specificity of training power output [119, 317] velocity [32, 80], and contraction type [23]. However, many of these studies have limited application for competitive athletes as they have used untrained subjects [10, 249], or single joint movements on isokinetic or isometric machines [28, 31, 55, 81, 102, 117, 164, 165, 194, 234, 241, 254], despite knowledge of different recruitment patterns inherent in different forms of contractions [86, 170]. These limitations raise questions regarding the validity and transfer of the findings of much of the published research on resistance training to athletic training programs. The literature is dominated by research on untrained subjects performing single joint, isometric/isokinetic training, because a regimented research approach in a laboratory setting is attractive for maintaining a high degree of experimental control [165]. While caution has been advised when applying their results to training sporting populations [255], practical applications of their findings in sport-performance outcomes continue to be inferred from laboratory-based training and testing [182]. As a result of researchers implicating their laboratory-based research in training active athletes, many strength and conditioning coaches design programs intended to improve the broad physical needs of team sport players based on research unproven in this population.

Some research studies in the area of resistance training involve trained athletes, but they are usually athletes with dedicated needs of muscle strength, power, or hypertrophy, such as powerlifters, Olympic lifters, or bodybuilders [178, 199]. Based on these shortcomings of previous literature and the high priority of resistance training in many team-sport programs [90, 91, 275], there is a need for additional research to advance our understanding of the underlying mechanisms and applications of resistance training for team sport athletes. To address these issues this thesis will investigate a resistance training design to improve strength, power, and hypertrophy through the use of ‘repetition failure’ and ‘forced repetitions’ [254, 288] (Study 4 and 5, Chapter 6 and 7). What is lacking from the literature is not the sport-specificity of resistance training research [44, 76, 80, 160, 196, 239] but the value of training to repetition failure and forced repetitions to improve sport-specific skills.

Unfortunately, the key training stimuli and underlying physiological mechanisms to develop muscular strength remain unclear. Proposed stimuli for maximal strength adaptation include tension on the muscle [304], eccentric tension [85], the amount of time under tension [270], prolonged exposure to metabolites [102, 270, 291], training volume [249] and fatigue [254]. Research of these factors has been difficult because analysis of kinetic properties typically requires expensive equipment and is not conducive to continual monitoring during training studies [95]. Recently, sensor technologies have emerged that are capable of continually monitoring free-weight bar movements, though the validity and reliability of these sensors is not well established [72, 155]. Cronin *et al.* [74] have validated optical encoders to measure force output during ballistic jumping, and found coefficient of variations ranging from 2.1% to 11.8% depending on the force characteristic measured (i.e. mean, peak, and time-to-peak force) and the type of jump performed (i.e. squat, counter-movement, or drop jump). Since force can be generated without actual movement, such a study would not validate the device's validity of measure displacement to derive movement velocity. Actual movement is an important characteristic when analysing free-weight resistance training, and is a necessary component of calculating work and power. Cronin *et al.* [74] only measured ballistic movements, but the optical encoder's validity may vary depending on movement speed. Therefore, an additional investigation in this thesis is to evaluate the validity of the Gymaware™ optic encoder in measuring a variety of movement kinematics, and use this device to characterise the magnitude of changes in movement kinetics as fatigue progresses over a commonly used training session design (Study 3, Chapter 5). If optical encoder technology proves to be a valid tool for measuring power, long-term analysis of parameters such as eccentric and concentric phase duration, and power decrement with successive repetitions would become more feasible.

2.4.3 Resistance Training To Improve Sport-Specific Power Output

Much of the research up to 1995 examined the concept of velocity/power specificity [29, 219, 264], leading to the recommendation for resistance training coaches to design programs for team-sport athletes involving low-fatigue, high-power training. However more recent research has demonstrated that improvements can be made in the performance of sport-specific skills with high-intensity resistance training despite relatively low training velocities (Tables 2.3 to 2.5). The apparently conflicting results between more recent studies and earlier research recommending velocity-specific training programs are related in part to the difference between laboratory- and field-based research. Research intended to improve athletic performance should be conducted on actively training athletes on multi-joint, free-weight resistance training protocols. Differences between velocity/power specific programs and higher resistance training programs tend to dissipate when sport-specific training is continued in actively training athletes, leading to several researchers to question the use of velocity/power specific training methods in elite sport [44, 75].

Power is the product of force and distance, divided by time. Therefore, to become more powerful, an athlete needs to develop the qualities of strength and speed. Kraemer *et al*. [184] found that 5 RM strength training improved both 1RM on upper (20%) and lower body (30%) strength tests, and peak and mean power on upper (10%) and lower (20%) body Wingate testing. Moss *et al*. [220] concluded that 1RM strength was important for power production after showing that heavy strength training (90% 1RM of elbow flexors) induced improvements at a broad range of resistances, even at loads as low as 2.5 kg, and elicited a strong (r=0.93) correlation between 1RM and maximal power. Power is particularly dependent on strength in sporting tasks that require power exerted against a large resistance [20, 196, 220]. A recent study by Liow and Hopkins [196] demonstrated that weight training improved kayaking performance when covering a 15 m distance by 3%. Improvements made using slow resistance training contributed mostly to the initial acceleration phase, improving 7% compared to the explosive training group, which improved by 3%. This research demonstrates that the benefits of resistance training were highest in the initial few metres after a stationary start as the athlete must overcome their own inertia [196]. Such a concept would apply regardless of the sport, from kayaking to basketball. Newton [223] came to a similar conclusion that the longer the slow phase of contraction the more important strength is to power development. Mero [212] found in trained 100-m sprinters that force production in the initial acceleration of a stationary start had a high correlation to the running velocity ($r=0.66$ $p<0.05$). Similarly, both Delecluse [80] and Balzevich [44] showed improvements in acceleration in sprinters after high intensity strength training. Finally, both Cronin [76] and Pick [239] assert that improving strength can improve power on the basis that muscle activation at the start of a movement is increased in stronger muscle. Strength plays a critical role in acceleration in overcoming the inertia of athlete's own body mass, which suggests the training of team sports should be heavily dependant on acceleration rather than speed.

While resistance training can assist training for some sport specific movements, it seems ineffective if there is no practice of the movement, such as weightlifters attempting to improve vertical jump with no practice of vertical jump [122]. Blazevich and Jenkins [44] demonstrated that high resistance and high power training groups had similar improvement in hip flexion torque, hip extension torque, squat strength, or 20-m sprint time (effect size of improvements range: 0.71, moderate to 1.05, large) for those subjects already involved in regular, frequent sprint training (6 sprint sessions/week). Both Jones *et al.* [160] and Delecluse *et al.* [80] showed that while heavy resistance training programs improved vertical jump in baseball players, and acceleration and speed in sprinters over 100 metres, respectively, superior improvements were made on the high velocity training protocol. Jones *et al.* [160] trained baseball players in the off-season while Delecluse *et al.* [80] investigated sprinters performing sprint training only one time per week, making these studies different to the work of Blazevich and Jenkins in the active training of sport-specific skills with the resistance training prescription. Taken together these studies indicate that strength training appears to enhance execution of specific skills only when the skill continues to be performed. This point was highlighted by Bobbert and van Soest [46] who indicated in a simulated model that vertical jump could be improved by 7.8 cm if squat strength improved by 20% providing jumping technique remained optimal: however a 2 cm decrease was observed when jumping technique was not optimized. Finally, Cronin *et al.* [75] demonstrated a 12.4% improvement in netball throw velocity in a strength training group of actively training netball players that was similar to the 8.8% improvement in a power training group. Therefore, strength does not appear to substantially correlate with tests such as paddling, jumping, sprinting, or throwing until the training program also includes frequent sport-specific training.

Despite the clear importance of strength in generation of power, individuals often cite anecdotes of low power in highly hypertrophied or strength trained individuals. There are several explanations for the reduced capacity to produce power in athletes on a dedicated hypertrophic training program. Very high volume hypertrophy training can increase the angle of muscle fibre pennation and decrease range of motion [165, 168]. Dedicated strength or hypertrophy trained athletes also lack specific training in power skills such as jumping or sprinting [223]. With minimal training of running and jumping skills, it naturally follows that there would be no substantial improvement of these skills. This scenario underlines the importance of continuing sport-specific training during a high-intensity resistance training program.

In actively training athletes, high power/velocity training programs and high resistance training programs typically improve power output to a similar extent, but high resistance training programs produce superior development of strength and hypertrophy [9, 44, 119, 165, 184, 196, 220, 279, 317] (Tables 2.3 to 2.5). Wilson *et al.* trained groups in strength, power, or plyometric training, they found that smaller, but still significant, improvements in almost all power tests were made by the strength group when compared to the maximal power group, but the maximal power group made no improvements in the force tests [317]. The potential for heavy resistance strength training to improve all three of strength, power, and hypertrophy makes such training generally more appealing to coaches of team sport athletes.

2.4.4 Summary of Benefits of Resistance Training to Athletes

Resistance training has been of benefit to injury resistance [130] in addition to performance in many sports including distance running [132], cycling [253], and sprinting [44, 80]. Resistance training can increase power output of sports-related skills such as throwing [75, 208] and jumping [46, 116, 120] when combined with actual training of skills or other ballistic training methods [18]. Mechanisms for improvement of explosive power events are not entirely clear but are likely linked to improving force production in the initial phase of acceleration in overcoming momentum [44, 196]. The benefits of combined skills practice with strength training are related to strength training improving force output while specific practice of the skill maintains skill execution and specific rate coding [75]. Specifically, benefits may be derived from improved activation, reduced coactivation, and reduced recurrent and autogenic inhibition [2], hypertrophy and improved strength [185], and muscle fibre conversion from IIb to IIa fibres [13, 242, 285]. For longer duration events such as cycling, sprinting, and team sport play, additional benefits may relate to increased levels of stored ATP, creatine phosphate, free creatine concentrations, glycogen storage [197] and the capacity of glycolytic enzymes [294].

2.5 Summary

A broad range of body sizes and fitness levels are evident in the different playing positions across most high-intensity intermittent team sports. Basketball is a sport where the body size and fitness level of players on the team will play a major role in determining competition success. While basketball is classified as a non-contact sport, body contact is common, particularly among the comparatively bigger players on the team. For these players, body mass and muscular strength are required to maintain nearly stationary positions when opponents contest for important positions under the basket. Relatively smaller players are responsible for carrying the ball quickly up the court and scoring points while defending their counterparts on the opposing team from doing the same. Speed, agility, and rapid recovery are critical fitness components of smaller players. Clearly, having favourable anthropometric and fitness characteristics is very important to success in basketball despite the highly skilled nature of the game. Nonetheless there is concern from some Australian national and international coaches regarding the possible declining fitness level of junior players entering State and National level basketball programs, and their capacity to improve the fitness of their players. A detailed understanding of differences between groups of players and changes for a given individual player over time would help coaches to better understand changing fitness levels over the short and long term.

Conventional wisdom holds that basketball players in every position should benefit from improvement of strength, power, and hypertrophy. In the past, team sport athletes avoided strength and hypertrophy programs, as the velocity and movement patterns of resistance training movements were too dissimilar to reproduce the velocity at which these athletes perform on the court or field [32]. Such a training philosophy ignores the role of force in the production of power, particularly when an athlete must exert power against high resistance or start moving from a nearly stationary position. Positions such as a basketball centre must exert their power against not only their own substantial inertia but also against another sizeable opponent. Low resistance, low volume, and low fatigue training focusing on power also ignore the importance of muscle mass in many team sports. Basketball forwards and centres require substantial strength and body size in order to exert high amounts of force under the basket, yet still require great speed and acceleration during transition plays to move quickly from one end of the court to the other. Such team sport athletes need a resistance-training program that develops body size, strength, and speed in a balanced and integrated approach. The conventional approach adopted by most team sport strength and conditioning coaches is to achieve this goal through a periodised training program that focuses on each component individually. Potential therefore exists for components to be trained together by using high fatigue to the point of repetition failure when sport-specific skills practice continues in actively training athletes.

Training that induces high fatigue has traditionally been considered useful for inducing hypertrophy as the impact of high repetition (moderate intensity) failure has been linked to muscular fatigue where low repetition (high intensity) fatigue is linked more to neural fatigue [30]. Therefore, athletes training strength generally participate in high intensity, low volume (i.e. low fatigue) training while those interested in muscular hypertrophy train high volume (i.e. high fatigue) [182]. These two distinct program types make developing a resistance training program for team sports athletes problematic. Neither a program dedicated to muscular size nor a program dedicated to muscular strength reflects the need of both muscular qualities in basketball players. Therefore a program with high intensity is needed for muscular strength and fatigue for muscular hypertrophy is needed. Fortunately, once researchers introduce sport-specific training to both the high power/velocity training group and the high resistance training group, differences between training groups on sport-specific tests become minimal[18, 46, 75, 116, 120, 208]. Reading the current literature in this light questions the application of velocity-specific training to training athletes [44, 75].

Resistance training 3-4 times per week with high fatigue to the point of repetition failure is unlikely to meet the goals of athletes with demands that are more unidimensional (e.g. powerlifters, bodybuilders, track sprinters). Critical analysis of the existing literature indicates there is sufficient theoretical and experimental evidence supporting the contention that training with sufficient fatigue to the point of repetition failure could be useful for developing hypertrophy, strength and power in team sport athletes.

2.6 Aims And Hypotheses

The general aim of this thesis is to systematically evaluate trends in the development of body size, strength, and power in highly trained (junior) basketball players, and to determine the relative effectiveness of resistance training programs employing repetition failure in developing these qualities. Five studies will be undertaken in highly trained junior basketball players to address these research questions.

The first study (Chapter 3) will involve quantifying the direction and magnitude of differences in fitness levels and anthropometric test scores of Australian junior basketball players, over a 6 year study period, related to recruitment age and recruitment year. The study will analyse an extensive retrospective data set compiled from past testing records of athletes from Basketball Australia, using mixed linear modeling. This study will also identify the value of fitness and anthropometric testing to the process of player selection to senior levels by comparing mean estimate scores with variation of athletes between tiers of the Australian competition system. Two hypotheses were tested:

Hypothesis #1: that discrete aspects of fitness of first-year players entering State and National junior levels have been declining in recent years; and

Hypothesis #2: that there will be a substantially greater fitness and body size, with lower variability in test scores, of senior ranked players relative to their lower ranked counterparts.

The second study (Chapter 4) will also involve using mixed linear modeling of the same extensive retrospective data set but quantify the magnitude of within-subject changes in fitness and anthropometric test scores. This analysis will assess mean changes in fitness and body size of Australian junior basketball players of different genders and levels of competition between phases of a competitive year and over multiple years. These data will also be used to indicate the expected amount of variation an individual player may experience around the predicted group means. Three hypotheses were tested:

Hypothesis #3: that players will show substantial improvement in body composition and fitness over multiple years in their respective programs;

Hypothesis #4: that there will be little improvement in body composition and fitness between individual phases of a year; and

Hypothesis #5: that there will be substantial individual variation from player to player.

While there is considerable potential for resistance training to improve the strength, speed, and size of basketball players, most of the current resistance training research is hampered by difficulties in quantifying key training variables such as power output and concentric time during a longitudinal training study. The third study (Chapter 5) will validate the use of an optical encoder (Gymaware™) to measure kinetic properties of Smith-machine back squats, Smith machine bench press throws, and free-weight bench press on such training variables total work and power output. This study will concurrently assess a variety of lifting techniques with both video and an optical encoder. Analysis of these data will involve calculating the Pearson Product Moment, standard error of the estimate, and coefficient of variation between the two measures [145]. This study will also investigate kinetic and kinematic changes that occur as fatigue develops during a typical bench press training session. The two hypotheses of this study were:

Hypothesis #6: that the optical encoder will be a valid tool of measuring power during free-weight resistance training activities; and

Hypothesis #7: that each phase of the concentric movement of the bench press movement will show substantial decreases in power output as consecutive bench press repetitions are performed.

The fourth study (Chapter 6) will contrast two bench press training programs of equal training volume, intensity, and duration but with one eliciting repetition failure while the other does not. The fourth study will assess elite junior basketball players, training to the point of repetition failure, to investigate if repetition failure makes a greater contribution to strength and power development than a non-failure design. The hypothesis of this study is:

Hypothesis #8: that training to the point of repetition failure will improve bench press strength more than a program not involving failure.

The purpose of the final study (Chapter 7) will be to elucidate if repeated sets of repetition failure (i.e. forced repetitions) commonly performed in many resistance training programs further contribute to strength, power, and hypertrophic gains, specifically investigating elite junior basketball players. Therefore, the fifth study will compare the effect of different set designs and volume on the magnitude of strength development when training with repetitions requiring the assistance of a spotter. The hypothesis of this final study is:

Hypothesis #9: that additional volume of forced repetitions will convey no further benefit to strength development than ceasing training at the point of repetition failure.

CHAPTER 3: MODELING AGE AND SECULAR DIFFERENCES IN FITNESS BETWEEN JUNIOR BASKETBALL PLAYERS

3.1 Introduction

Several anthropometric and fitness tests, common to basketball programs throughout Australia [284], are often used by coaches in recruiting new players into State and National programs. Despite previous studies in basketball linking anthropometric and fitness test scores with level of play [211], player success [14, 134], playing time [140], position [191], and team success [113], the information available for coaches is limited to basic descriptive statistics collected on small samples of basketball players [7, 25, 137]. Very few studies go beyond one year [151, 190] or have greater than 100 athletes [36, 172, 191] thereby limiting their statistical power. Interpreting results from studies using large numbers of players in different locations is often difficult due to differences in test protocols [191]. Development of detailed reference values for test scores for players of different age groups, genders, and competitive levels are required to allow coaches to set appropriate fitness goals for specific groups of junior basketball players.

Although fitness improves through the adolescent years [258], there is a trend in recent decades towards declining fitness in Australian school children [299]. This latter trend is generating concern in the public health and sporting communities. There has been no exploration of how trends in the general population compare to the fitness levels of adolescents recruited into high-level sporting programs, although anecdotal reports from coaches suggests a trend of declining fitness in junior Australian basketball. Of particular interest are the secular trends of anthropometric and fitness test scores in the recruitment of new players to the State and National levels. Examination of secular trends would prove valuable information for coaches and administrators to help them clarify whether fitness trends in the general population are affecting fitness levels of basketball players entering elite programs, assess the value of prior recruitment patterns, identify important anthropometric and fitness factors in recruitment for elite programs, and enhance the physical preparation of players at junior levels.

Team sports typically encompass a wide variety of anthropometric and fitness characteristics in order for players to play different positions in the game, and basketball is no exception [301]. While some variation between athletes is expected, establishing reference ranges for between-athlete variation in both anthropometric and fitness test results would allow coaches to identify exceptional results for talent identification purposes and assign remedial fitness training and goal setting. The aims of this study were to determine the effects of age, gender and competitive level on anthropometric and fitness test scores in junior basketball players, and identify secular differences in recruitment patterns over an eight-year period.

3.2 Methods

3.2.1 Subjects

The sample comprised 1011 females (904 State players, 107 National players) and 1087 males (958 State players, 129 National players) entering Basketball Australia (BA) State and National training programs. Athlete test scores were obtained during regularly scheduled fitness testing between 1996 and 2003 inclusive. Individual athletes were tested 2.6 ± 2.0 (mean ± SD) occasions over 0.8 ± 1.0 y. The age of the four groups were: National males 17.1 ± 1.0 y (range: 15-19), National females 16.7 ± 1.2 y (14-19), State males 15.7 ± 0.9 y (13-20) and State females 15.5 ± 0.9 y (13-21).

Subjects (or parent/legal guardian) provided written informed consent for testing, training, data collection, and publication of results as part of their Scholarship Agreement with the Australian Institute of Sport (AIS) and/or BA Intensive Training Centre (ITC) programs.

3.2.2 Experimental Design

Junior sport typically functions in a tiered system where the better players at a particular level graduate to the next higher level, moving from local competitions to State, and eventually National teams. All National subjects participated at National Under-16 and Under-18 Men's and Women's Australian Junior Camps, and/or were on full-time scholarships with the AIS Men's and Women's Basketball teams. State players trained at one of seven State or Territory ITC Programs around Australia. Tests were conducted in accordance with test protocols prescribed by the national sporting body [284]. Testing group sizes ranged from 5 to 70 athletes but were typically 10-14 players, approximating the size of a basketball team. All results were compiled from the records of routine fitness testing conducted on players at each state ITC, at the Australian Junior Camps, and the AIS.

3.2.3 Description of Tests

3.2.3.1 Anthropometric Measurements

Athlete stretched height and body mass were measured using a stadiometer and digital scales respectively. Typical error of measurement (TEM) [147] for measuring both height and body mass, including biological variation, is typically not more than 1% [229]. Skinfolds measurements comprised the sum of seven skinfold thicknesses from triceps, subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf measured with a TEM typically <3% for intertester variability [229].

3.2.3.2 Fitness Tests

Two maximal effort tests were used to measure leg power: 20-m sprint and vertical jump [284]. The fastest of three attempts of elapsed movement time from a stationary standing start to a 20-m point was recorded using electronic light gates (SWIFT Performance Equipment, Lismore, Australia). A vertical jump test measured the best of three maximal counter-movement jump heights allowing a single backward step using a YardStick vertical jump apparatus (SWIFT Performance Equipment, Lismore, Australia). The aerobic fitness test was a 20-metre shuttle run test involved running repeated 20-m long straight lines at a progressively faster pace set by a recorded tone until the athlete could no longer run in rhythm with the tone [247]. Athletes had performed these tests many times prior to testing at State- and National-levels so there was an assumption of a minimal learning effect in the results.

3.2.4 Fitness Test Reliability

Data collectors were employed by the sports institutes, Basketball Australia, or were privately contracted to collect fitness and anthropometric data and were therefore competent to perform testing. For consistency and specificity, all fitness testing occurred on basketball court floors. The TEM was established with a series of test re-test reliability trials [147]. A subgroup of 24 male and female National level players completed duplicate tests within 5-7 days under standardized conditions. Results were analyzed as the square root of 2 of the within-subject standard deviation (i.e. TEM= $\Delta SD/\sqrt{2}$).

3.2.5 Statistical Analyses

Log transformation and repeated-measures mixed linear modeling using Proc Mixed in the Statistical Analysis System software (Version 8.1, SAS Institute, Cary, North Carolina, USA) provided estimates of percent differences in means (fixed effects) and between- and within-athlete coefficients of variation (CV) (random effects) for each fitness and anthropometric test. Separate analyses were performed for each gender at each level (i.e. State Female, National Female, State Male, and National Male).

The fixed effects in each analysis were Year, Year*Year, Age, and Age*Age, where Year was a numeric between-subject effect representing the calendar year when each player was recruited (1996 - 2003), and Age was a numeric between-subject effect representing the age of the player when they were recruited into their respective level of play (14 – 19 y). Quadratic effects for Age, and Year were included in the model as the simplest approach to allow for non-linear effects of these predictors.

The random effects in the analyses were Athlete and the residual, where Athlete was the identity of the athlete (to estimate pure between-athlete variance). Means for different age of recruitment were adjusted to the year 1998. Means for calendar years of recruitment were estimated without adjustment for age by using a simpler fixed-effects model, in which Age was omitted.

We compared mean estimates for a given anthropometric or fitness test at different ages of recruitment by calculating the Cohen, or standardized, effect size (ES), defined as (difference in means)/SD [68]. Cohen regarded 0.1, 0.3, and 0.5 as the thresholds for small, moderate, and large correlations respectively [68]. These thresholds actually correspond to effect sizes of 0.20, 0.63, and 1.16, and not 0.2, 0.5, and 0.8 as suggested by Cohen. We did not regard Cohen thresholds as definitive [68], so we used effect sizes of 0.2, 0.6, and 1.2 as thresholds for small, moderate, and large effects. For the sake of parsimony only effects that were at least moderate in size are reported (ES >0.6). The likelihood that the true value of estimated difference in fitness and anthropometric tests were larger than the smallest worthwhile (practical) difference was calculated. Thresholds for assigning qualitative terms to chances are described in Table 3.1 [196]. Differences in means between groups were expressed with 95% confidence intervals (95%CI).

To compare the magnitude of variation in a given anthropometric or fitness test score between levels for each gender, the National standard deviation was divided by the State. Ratios within a range of 0.9 to 1.1 were considered trivial (see justification at http://yahoogroups.com/groups/sportscience/message/2538); ratios >1.1 indicate test scores in National athletes were substantially more variable than in State athletes, whereas ratios <0.9 indicate test results in National athletes were substantially less variable.

3.3 Results

3.3.1 Fitness Test Reliability

Reliability testing was conducted only on National-level athletes. The shuttle run had the highest TEM of 4.1% (0.4 levels), where the 20-m sprint test TEM was 1.3% (0.04 s), and the vertical jump TEM was 1.4% (0.5 cm).

3.3.2 Level (State versus National)

National-level players, regardless of gender, were better than State-level players on all anthropometric and fitness tests, with effect sizes ranging from 0.02 (trivial) to 0.80 (large). Differences between levels were generally small except male height (7 cm, 95%CI ±3.4 cm, ES moderate) and male body mass (6.7 kg, 95%CL ±4.0 kg, ES moderate). Standardized differences in means between levels are summarized in Table 3.1.

Variation within the National and State groups on any given test, as estimated by the between-subject coefficient of variation (CV), tended to be similar, with National groups being slightly less variable. Ratios comparing National to State CV (i.e. National/State) show that the variation was higher only in National players in male vertical jump (1.14) and female height (1.18). Ratios of less than 1.00, indicating State variation exceeded National variation, were evident in the male shuttle run (0.84), female skinfolds (0.86), and male sprint (0.83). Variation between female groups was similar for the 20-m sprint (0.99) and body mass (1.00). While State variation exceeded National variation on all other tests, differences were generally trivial (0.92 to 0.95). Estimations of all between-group ratios showed a similar degree of uncertainty (×⁄÷1.10). Typical variation is expressed using a ×⁄÷ factor (e.g. ×⁄÷1.10) rather than a ±% factor (e.g. ±10%) because in log-normally distributed variables, typical variation is better described with a ×⁄÷ factor when the variation is more than a few percent. For example, 100 units ×⁄÷2.00 is not ±100%, but +100% (i.e. 200 units) or –50% (i.e. 50 units).

Table 3.1 - Differences between levels of players

Effect sizes and qualitative descriptors of differences between levels of players (State vs National). Positive values of the effect size indicates National scores were greater than State. In skinfold and sprint tests, lower scores are better. Probability reflects the likelihood that National level players were at least a small effect size better (>0.2*SD) than State level players.

Test	Gender	Mean Score ± SD		Magnitude of National - State Effects		
		State	National	Effect Size ±95%CI	Qualitative Descriptor[a]	Chances of National better than State[b]
Vertical Jump (cm)	F	45.6 ±6.5	45.7 ±6.1	0.02 ±0.37	Trivial	17%: unlikely
	M	59.1 ±7.3	62.0 ±8.4	0.36 ±0.40	Small	78%: likely
Shuttle (levels)	F	9.3 ±1.6	10.0 ±1.4	0.47 ±0.41	Small	90%: likely
	M	11.2 ±1.6	11.6 ±1.4	0.29 ±0.40	Small	67%: possibly
Skinfolds (mm)	F	103.4 ±28.3	95.9 ±24.3	-0.28 ±0.36	Small	67%: possibly
	M	68.4 ±22.3	67.5 ±20.6	-0.04 ±0.36	Trivial	19%: unlikely
Sprint (s)	F	3.42 ±0.16	3.38 ±0.16	-0.25 ±0.46	Small	59%: possibly
	M	3.15 ±0.16	3.08 ±0.13	-0.47 ±0.45	Small	88%: likely
Mass (kg)	F	65.6 ±8.6	69.6 ±8.5	0.47 ±0.37	Small	93%: likely
	M	77.3 ±11.0	84.0 ±10.3	0.63 ±0.38	Moderate	99%: very likely
Height (cm)	F	174.3 ±7.0	177.9 ±8.3	0.47 ±0.38	Small	92%: likely
	M	187.8 ±8.9	194.8 ±8.5	0.80 ±0.40	Moderate	100%: definitively

M=male, F=female; 95%CI: 95% confidence interval of the true effect size

[a]Criteria for magnitude: <0.2 trivial, 0.2 – 0.6 small, 0.6 – 1.2 moderate, > 1.2 large

[b]Thresholds for assigning qualitative terms to chances of substantial effects were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; >50%, possibly; >75%, likely; >95%, very likely; >99% almost certain.

3.3.3 Gender

In both National and State levels, males scored better than females on all anthropometric and fitness tests with effect sizes ranging from 1.1 to 2.1. Substantially more variation existed among females than males only for skinfolds (by a factor of 1.23) while males had more variation in vertical jump (1.25), mass (1.25), and height (1.13). Variation between genders was similar for sprint time (1.06) and identical in shuttle run (1.00). The uncertainty of estimates of all ratios of variation between genders was ×⁄÷ 1.10.

3.3.4 Age Differences at Recruitment (14-19 y)

3.3.4.1 Anthropometry

All data are expressed in Figure 3.1A-C. While there was a trend for older players to have more favorable anthropometric test scores when recruited into their first year of State and National programs, the higher test scores of older athletes occasionally plateaued or reversed at approximately 17 y. National groups showed the greatest difference in height between older and younger players, with older athletes being taller between 14 and 17 y (standardized effect sizes, ±95% CI of ES: female: 0.93, ±0.93; male: 0.66, ±1.20). For the older juniors the height of females entering National programs declined between 17 and 19 y (0.55, ±0.93). The height difference for State players continued to increase up to 18 y (males: 1.15, ±0.54; females: 0.54, ±1.57) (Figure 3.1A). Given the substantial amount of uncertainty in some estimates, estimating growth differences in this age group is understandably imprecise.

Body mass between 14 and 17 y was higher in newly recruited older females with older players being heavier (National: 1.89, ±0.80; State: 0.73, ±0.44). However, between 17 and 19 y the older National players were lighter (1.05, ±0.87). Older male athletes had greater body mass in their recruitment year in both levels between 14 and 19 y males (National: 0.76, ±1.39; State: 2.13, ±1.54) than younger players (Figure 3.1B).

Skinfolds were higher in older National females between 14 and 17 y (1.15, ±1.54) but were lower in older athletes between 17 and 19 y (0.64, ±0.94). While older National males were lower in skinfolds comparing 14 and 19 y (0.80, ±1.39), older State females were higher (1.00, ±1.31) in skinfolds over the same age range (Figure 3.1C).

3.3.4.2 Fitness

There were also variable patterns in fitness tests between the different ages of recruitment. In general, better fitness was observed in older players (Figure 3.1D-F). For National females, players recruited at 14 y jumped 4.5 cm higher (0.75, ±1.07) than 17 y athletes, but older 19 y male athletes jumped higher than 14 y players (National: 0.76, ±1.12; State: 1.13, ±0.54, Figure 3.2) (Figure 3.1D).

Older State male players up to 17 y had faster sprint times when recruited than 14 y (0.74, ±0.42) (Figure 3.1E). The younger National female 14 y group scored 1.7 levels higher on the shuttle run than the 17 y (1.17, ±1.38) when recruited, though there was substantial restoration of this difference comparing the 17 y group to 19 y (2.09, ±1.68). State male 16 y athletes had higher scores than 19 y (0.69, ±1.07) while older 18 y National male players had higher shuttle run scores than 14 y (1.67, ±1.96) (Figure 3.1F).

Figure 3.1 – Age trends in group fitness

Group estimates for National Females (●), National Males (■), State Females (○), and State Males (□) showing the scores of different groups throughout the age range, adjusted to recruitment year 1998. Error bars represent 95% confidence limits while the filled bars (▮) represent the typical error of measure for the test and the open bars (▯) represent the between-subject SD averaged over all groups. Group means have been slightly offset from age for clarity.

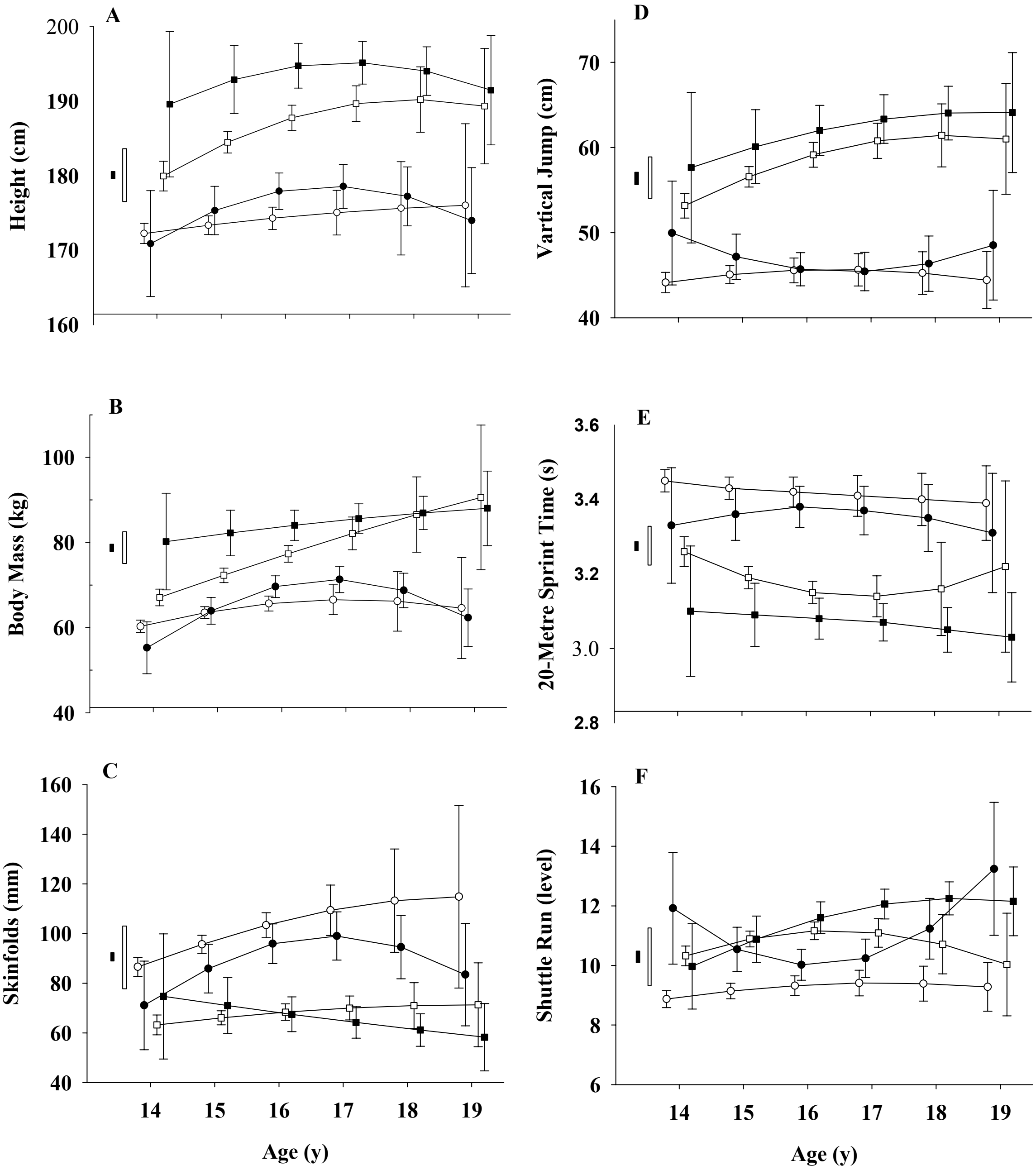
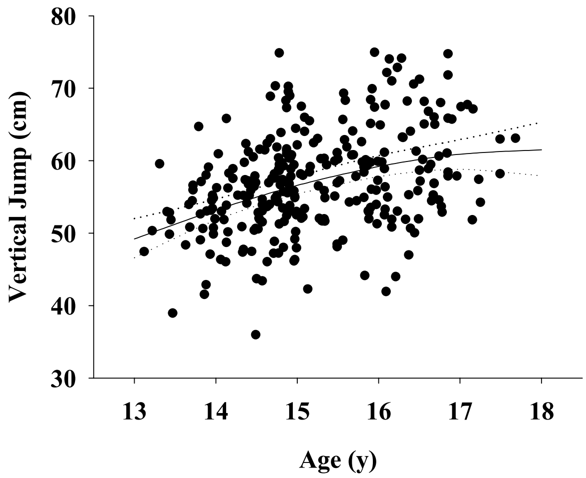


Figure 3.2 - State male vertical jump
Scatter plot to illustrate additional detail to the origins of the State Male plot of Figure 1D, indicating the age trend of State male vertical jump (N=1164). This figure represents a typical plot for the age effect of any test, showing the distribution of individual players and the mean trend line from 13 to 19 y of age. In this example, older State Male players are jumping higher than younger players. The graph plots individual player test scores (●) while the solid trend line refers to the modeled estimate over time, and the dotted lines (……) refer to the upper and lower 95% confidence limits for the true mean.



3.3.5 Secular Differences (1996-2003)

3.3.5.1.Anthropometry

All anthropometric data are shown in Figure 3.3A-C. There was little change in anthropometry scores in players recruited between 1996 and 2003, and any differences that existed tended to be small. Between 1999 and 2003, successive groups of National females had lower skinfolds (standardized effect sizes, ±95% confidence interval of ES: 0.89, ±0.63) and height (0.58, ±0.69), with newly recruited National males also showing lower skinfolds (0.65, ±0.65) in 2003 (Figure 3.3C).

3.3.5.2 Fitness

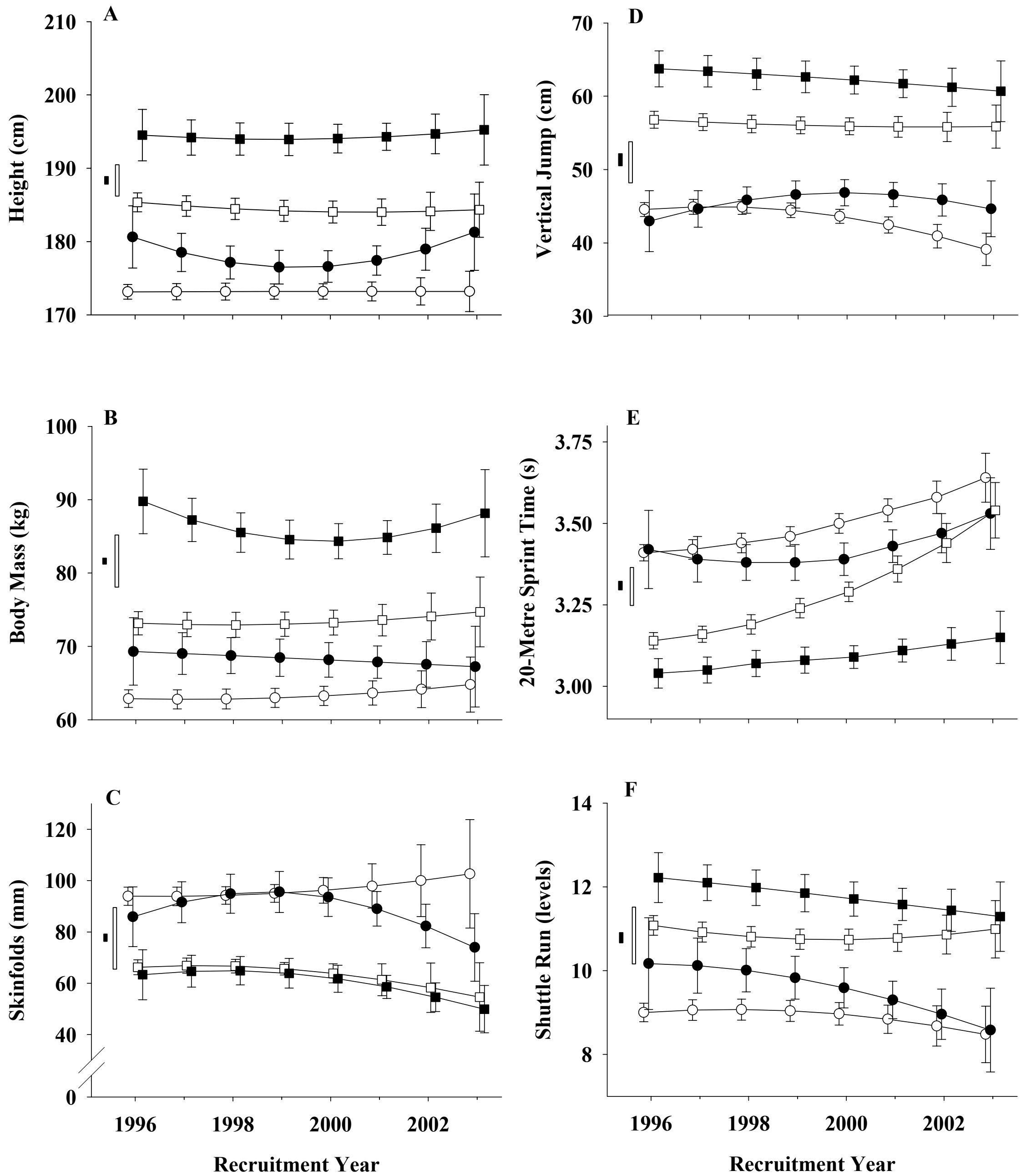
There was a general decline in the quality of fitness test scores between newly recruited players during the study period, although scores did not decline uniformly for all groups on all tests. Between 1996 and 2000, successive cohorts of National females increased jump height (ES: 0.64, ±0.75) while State females experienced a decline in jump height (0.83, ±0.38) (Figure 3.3D). Both National groups experienced a reduction in the quality of sprinting, with increases in 20-m sprint time (females: 0.70, ±1.04; males: 0.82, ±0.69). The slowing in sprint times over the study period in State athletes was at least twice that of National athletes (National Female: 0.70 ± 1.04; National Male: 0.82 ± 0.69; State Female: 1.45 ± 0.50; State Male: 2.47 ± 0.55) (Figure 3.3E). The magnitude of the increase in sprint time performance was similar to the decline in aerobic fitness over the same period. Shuttle run scores were lower in both National groups (female: 1.11, ±1.03; male: 0.68, ±0.74) in 2003 than in 1996 (Figure 3.3F).

3.3.5.3 Age

The age of players at recruitment declined for both the male and female National teams over the study period, with females declining from 17.5 ± 0.9 y to 16.3 ± 1.3 y (-1.2 y, 95%CL ±0.8 y) and males declining from 18.1 ± 0.2 y to 16.2 ± 1.0 y (-1.9 y, 95%CL ±0.8 y). State groups also declined in age but to a lesser extent. Female age declined from 15.4 ± 1.1 to 14.8 ± 0.9 (-0.6 y, 95%CL ±0.4 y) and males from 15.6 ± 1.0 to 14.9 ± 1.0 (-0.7 y, 95%CL ±0.4 y).

Figure 3.3 - Age trends in group fitness

Group estimates showing actual trends for National Females (●), National Males (■), State Females (○), and State Males (□) comparing year of recruitment between groups. Error bars represent 95% confidence limits while the filled bars (▮) represent the typical error of measure for the test and the open bars (▯) represent the between-subject SD averaged over all groups. Group means have been slightly offset from the designated year for clarity.



3.4 Discussion

The current research is the first study to comprehensively assess the effects of recruitment age and recruitment year on fitness and anthropometric testing in junior basketball. This chapter has examined the results of a standardized battery of tests on male and female players at different levels of competition with greater than 1,000 subjects over an 8-year period. There have also been systematic comparisons of group means in anthropometric and fitness test results between junior male and female basketball players, State- and National-level players, players of different chronological ages, and players recruited in different calendar years. Estimated means varied at different ages for different groups, with test scores tending to be better for younger juniors at recruitment age 14-17 y than older juniors age 17-19 y. While anthropometric measures were largely unchanged in recent calendar years, the speed and endurance of players have generally declined by at least small amounts. The National males and females had better scores with lower variation than State players indicating that the test protocols have potential use for talent identification purposes.

3.4.1 Age Differences at Recruitment

Older athletes generally scored better in anthropometric and fitness tests with greater improvements observed in National level players. The lower skinfolds and higher body mass with older recruitment age in the National Male group probably reflects greater development of muscle mass. This contention is supported by the higher power-to-body-mass ratio evident in improvements in vertical jump and sprint time. In State Males, the unfavorable differences in shuttle run and sprints in older players after 17 y are indicative of a poorer power to weight ratio associated with increasing skinfolds. The opposite trend can be seen in the female groups with National females decreasing skinfolds and improving fitness test scores, particularly beyond 17 y. The more favorable National player's anthropometric and court measures with age implies that these players are fitter, likely as a consequence of more extensive and intensive physical conditioning associated with this level of program, especially beyond 17 y. State players participate in part-time training programs and generally do not undertake the comprehensive physical conditioning programs of their full-time National counterparts. Consequently State players exhibit typical adolescent gains in height and body mass but not the same magnitudes of improvements in skinfolds and measures of fitness as National-level players. The magnitude of difference between younger and older basketball players in State players in vertical jump was somewhat less than the difference in basketball players of the same ages (13 to 19 y) in other research (ES males: 1.13 versus 2.10; ES females: 0.05 versus 0.52) [172].

The decline in height of National players between the recruitment age of 18 and 19 years does not indicate that individuals in this group decrease height with age, but that newly recruited players are on average shorter than newly recruited 16- and 17-year-old players. National players in the 14-17 year old age category may be recruited heavily on the basis of height, while older players are selected more on the basis of skill. Most of the taller players appear to have been recruited already by 17 years of age.

3.4.2 Secular Differences

The values of the test results in the current study represent the outcome of recruiting practices in State and National programs. Variable trends in anthropometry and fitness test results over the eight calendar-year period were observed: some test results showed improvement, some were relatively unchanged, and others showed a small decline. Clearly there has been a conscious decision of National female coaches to recruit taller players. There was a trend for declining body mass in both National groups, though effects were small, and skinfolds showed moderate decreases in three of the four groups studied. Comparing 2003 to 1996, most group characteristics remained stable or showed decrements in vertical jump, 20-m sprint and shuttle run performance. These findings confirm anecdotal reports that some aspects of fitness in newly recruited junior players have declined in recent years. Clearly basketball authorities need to address these important issues of player recruitment and fitness levels in junior programs as even very small changes in performance can have substantial implication for sports performance at the elite level.

We have also found a trend toward recruitment of younger players in both National and State programs in recent years. This trend is concerning because younger players tend to be less fit, particularly below 17y. The secular decline in fitness can be partially attributed to the decline in age of recently recruited players. Potential strategies for improving fitness levels in the future would include greater fitness development of younger players at lower levels (e.g. school and local club leagues), in addition to be to recruiting players close to the upper limit of their age group, though care should be taken not to overlook the early development of young tall players solely in the interest of gaining fitness.

3.4.3 Program Level and Gender Differences

The National level players were generally bigger and fitter than State players. While most Cohen effect sizes were considered ‘small’ (Table 1), the effect is consistent across all but two comparisons (i.e. male skinfolds and female vertical jump).The higher test scores likely reflect the National players' greater commitment and intensity in training and possibly higher genetic capacities for these tests. These differences may be a result of greater muscle mass in National players, as reflected in greater body mass yet lower skinfolds. Fitter players may also be able to perform better during team selection camps. The current results are in accordance with studies such as Hoare [134], who concluded that anthropometric and fitness tests accounted for ~40% in variance of playing performance, and Hoffman *et* al. [140] that predicted that fitness test scores accounted for up to 20% of playing time when the athlete was well known to the coach or up to 80% if the athlete was not known. Collectively this evidence underscores the importance of well developed fitness attributes for junior basketball players.

The differing anthropometric characteristics between groups may reflect simply variations in biological maturity and/or the recruitment strategies of coaches, with the greater fitness levels of National players reflecting greater biological maturity. While there were no direct measures of biological age in this study, the height of National players plateaued one year earlier than the State level players, possibly indicating that the National players had reached biological maturity one year earlier then the State level players. Inspection of the fitness test results at 19 years-old, presumably when both groups had reached biological maturity based on stability of height, reveals National players were superior. It seems that regardless of biological maturity, National-level players remain bigger and fitter than State-level players.

The difference between males and females is consistent with previous data showing adolescent males are typically taller and heavier [201], have between 5-20% higher aerobic capacity [38], and score at least one standard deviation greater on most tests of fitness [38]. Particularly large magnitudes in differences between males and females were evident in vertical jump, skinfolds, and body mass reflecting an greater ratio of power to body mass of males in this age group [258]. These gender differences are explained by the natural difference in biological maturation, with males having a longer pubertal growth period and faster peak height and body mass growth [258]. Coaches of junior athletes should therefore expect increasingly large differences in anthropometric and court test scores between the genders as adolescence progresses.

3.4.4 Implications of Test Variability

Quantifying the variability of different tests allows coaches and sport scientists to evaluate the usefulness of a test. A test needs a typical error of measurement of less than 0.20 of the test's between-athlete standard deviation in order to provide confident assessment of small (worthwhile) differences between athletes [147]. While TEM of height and body mass are reasonably well established [229] and TEM of skinfolds is specific to each individual tester, the TEM of fitness tests needed to be established and included in interpretation of results. On the basis of the current results comparing the magnitudes of typical error of measure and between-athlete variability, all of the tests examined in this study are capable of identifying meaningful differences in fitness and anthropometric characteristics between athletes. Furthermore, the National groups had higher mean scores on all tests with lower variability on most tests, underlining the value of these tests as an athlete selection tool.

The low percent variation in height (~4.5%) was initially surprising, given the apparent range of height in the different positions in basketball. However a variation of 4.5% is equivalent to 7.8 cm in the mean height of females and 8.5 cm in males, so this magnitude of variation is not unexpected. The considerable variation in body mass, skinfolds, and shuttle run likely represents differences between the demands of different positions in basketball. Anthropometric testing may be useful for assigning players to particular positions or assessing the effectiveness of dietary practices and strength and conditioning programs. The small variation in sprint times indicates that this characteristic is relatively homogeneous, although a 4.8% variation of 3.1 s represents 0.15 s, which over 20 m equates to a displacement of 90 cm, potentially a critical distance on a basketball court. The estimate of the smallest worthwhile difference is ~ 0.04 s, equivalent to a distance of approximately 20 cm.

The basketball community must also consider individual variation in size and fitness of players, even at the elite level. The classic example often cited as the exception to the trend of basketball players being large is Spud Webb, who, despite being only 167 cm tall and weighing only 60 kg, played 12 seasons in the American National Basketball Association (NBA). Doubtless there are many other examples of extraordinary players who could easily have been overlooked if anthropometric and fitness test scores were the sole criteria for selection. Clearly a range of sport-specific methods should be used to assess basketball players [303] but current results confirm the findings of other studies supporting the use of anthropometric and fitness testing for team sports [134, 135, 240]. This research does not profess that fitness is the only measure of basketball success, nor that fitness should be the most import determinant in a coach’s selection of players. The experimental findings also indicate that predicting basketball success cannot be simply based on anthropometric and fitness test results. The thesis conclusions are focused on the findings that a higher level of fitness is a consistent characteristic of players in a higher level of competition.

3.5 Conclusions

This research utilized a very large sample size to quantify the magnitude of a variety of effects on elite Australian junior basketball players' anthropometric and fitness test scores. There was an overall large effect of gender and a small, but still meaningful, effect of competition level. The more favorable scores with lower variability at higher levels indicated the value of fitness tests as a talent identification tool. The pattern of overall declining test scores and player age of Australian basketball players over an eight year study period is a major issue for contemporary basketball. Coaches must consider the age of players they are selecting and the effect this will have on player fitness levels. The value of fitness and anthropometric testing is demonstrated by the National level players having better scores with lower between-subject variability. Basketball organisations and individual teams should benefit from the administration of anthropometric and fitness testing to junior players.

CHAPTER 4: CHARACTERIZING CHANGES IN FITNESS OF BASKETBALL PLAYERS WITHIN AND BETWEEN SEASONS

4.1 Introduction

When young athletes begin a fitness training program, improvements are typically rapid, but changes become less dramatic after the initial adaptations [216, 263, 266]. For athletes with a large training background, fitness can be relatively stable, increase, or decrease depending on the volume, intensity, and periodization of the training program [113, 141]. While fitness analysis on small groups of basketball players has been conducted within a competitive season [138, 141] and during the transition from the pre-season to in-season season [141, 293], analysis over an entire competition year or over several years on a large number of basketball players is logistically difficult [151] and unreported in the exercise literature. Most of the previous research assessing fitness changes in basketball players have study periods of less than one year and conducted on small (≤40) numbers of athletes [151].

Basketball is a court game where individual skill and team play are generally considered the key determinants of success. Consequently, the physical fitness of players is normally not a primary outcome of training compared with individual sports such as running, cycling, swimming, and triathlon. In many higher level basketball programs, specific fitness conditioning is reduced to a bare minimum during the in-season phase [141]. In American collegiate pre-season basketball training players can improve anaerobic capacity and body composition, with little change in aerobic conditioning [293]. During the in-season phase, player fitness levels typically remain stable or may even decrease after several weeks or months of reduced training [141].

The detraining effect of the in-season phase has been linked to players with a low amount of playing time, with reserve or substitute players experiencing detraining but starting players maintaining fitness [62]. This scenario is in accordance with the widely held belief that fitness is at best maintained during the in-season phase [139] though this may not be the most effective way to periodize a program [114, 139].

Anthropometric and fitness test scores have been previously linked with individual player success [14, 134], playing time [140], position [191], and team success [114]. This research showing the importance of anthropometric and fitness tests has increased the interest of coaches in the relative effectiveness of changing fitness on various outcomes of playing success. However studies are required to identify the influence of gender and competitive level on the magnitude of changes of anthropometric and fitness test scores within seasons and over multiple years utilising a large number of players.

The purpose of this study was to determine the magnitude and pattern of changes in fitness and body size of players in Basketball Australia's junior high-performance training programs between phases of the year (early-, mid-, and late-season) and with the amount of time spent in the program (first-, second-, and third-year players). A second purpose was to quantify the amount of variation an individual may have around the estimated mean group response. The comprehensive battery of anthropometric and fitness tests administered several times per year in most Basketball Australia junior programs has allowed pooling and retrospective analysis of test results from males and females across a range of ages in both State and National level programs over several years.

4.2 Methods

4.2.1 Subjects

Our subjects comprised State- and National- level players participating in organized programs of Basketball Australia (BA) and the Australian Institute of Sport (AIS). All National subjects participated at National Under-16 and Under-18 Men's and Women's Australian Junior Camps, and/or were on full-time scholarships with the AIS Men's and Women's Basketball programs. The State subjects were members of one of the ten Basketball Australia's Intensive Training Centre Programs (ITC) administered by each of Australia's States and Territories. The study sample comprised 1011 females (904 State players, 107 National players) and 1087 males (958 State players, 129 National players) assessed during regularly scheduled fitness testing over a seven-year period. The age (mean ± SD) of the four groups were: National males 17.1 ± 1.0 y (range: 15-19 y), National females 16.7 ± 1.2 y (range14-19 y), State males 15.7 ± 0.9 y (13-20 y) and State females 15.5 ± 0.9 y (13-21 y). Subjects (or parent/legal guardian) provided written informed consent for testing, training, data collection, and publication of results as part of their Scholarship Agreement with the AIS and BA ITC programs. All procedures undertaken in this study were routinely encountered within the training environment and approved by the Ethics Committee of the AIS.

4.2.2 Experimental Design

During the study period, junior basketball in Australia operated in a tiered system where the better players at a particular level were selected to the next higher level, and moved from local competitions to State, and eventually National teams. Training scholarships generally had a duration lasting between one and three years. Fitness and anthropometric test trials were typically conducted three times per year at regular intervals. Tests were conducted in accordance with test protocols prescribed by the national sporting body [284]. Testing group sizes ranged from 5 to 70 athletes but were typically 10-14 players, approximating the size of a basketball team. All results were compiled from the records of routine fitness testing conducted on players at each State ITC, at the Australian Junior Camps, and the AIS.

Fitness testing consisted of assessment of aerobic fitness (20-m shuttle run) and power (vertical jump and 20-m sprint). Anthropometric testing involved assessment of height, body mass, and sum of seven skinfolds [284]. Players were grouped by gender and then by level of play (State versus National). Fitness and anthropometric testing results for each player were then categorized by the phase of the year (early phase = January-April, middle phase = May-August, or late phase = September-December) and the length of time the player had completed (years in the program). Phases of the year were selected to represent the standard State-level basketball season undertaken during the Australian school year. Organizing data in this fashion allowed us to assess individual player changes within a calendar year (i.e. between phases of the year) and over multiple years in the program. Differences in these changes between males and females, and National and State level players were also assessed.

4.2.3 Description of Tests

4.2.3.1 Anthropometric Measurements

Anthropometrists, qualified to a minimum of Level 1 with the International Society for the Advancement of Kinanthropometry (ISAK), collected all anthropometric data. Stretched height was measured during inspiration using a stadiometer (Holtain Ltd.

Crymych, Dyfed). Typical error of measurement (TEM) [147] for measuring height, including biological variation, is typically not more than 1% [229]. Beam balance or digital scales were used to measure body mass to the nearest 0.1 kg with a TEM between days, including biological variation, of 1% [229]. Skinfolds comprised the sum of seven skinfold thicknesses from triceps, subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf measured with Harpenden calipers (British Indicators Ltd., West Sussex, United Kingdom), with a TEM typically <3% for intertester variability [229].

4.2.3.2 Fitness Tests

Two maximal effort tests were used to measure leg power: 20-m sprint and vertical jump [284]. Players had performed these tests many times prior to testing at State- and National-levels, so a minimal learning effect was assumed. The fastest of three attempts of elapsed movement time from a stationary standing start to a 20-m point was recorded using electronic light gates (SWIFT Performance Equipment, Lismore, Australia) with a TEM of 1.3%, or approximately 0.04 s. A vertical jump test measured the best of three maximal counter-movement jump heights allowing a single backward step, similar to a player's movements in a jump-ball, using a YardStick vertical jump apparatus (SWIFT Performance Equipment, Lismore, Australia) with a TEM of 0.5%, or approximately 1.4 cm. The aerobic fitness test [247] involved running repeated 20-m straight lines at a progressively faster pace set by a recorded tone until the athlete could no longer run in rhythm with the tone with a TEM of 4.1%, or approximately 0.4 levels.

4.2.4 Fitness Test Reliability

The typical error of measurement was established with a series of test re-test reliability trials [147]. A subgroup of 24 male and female National level players completed duplicate tests within 5-7 days under standardized conditions. Results were analyzed as the square root of 2 of the within-subject standard deviation of the difference scores between the two trials (i.e. TEM= $\Delta SD/\sqrt{2}$). The typical error for the current testing protocols has been detailed elsewhere, but is expressed here in Figures 4.1 and 4.2 in order to illustrate the magnitude of change relative to normal variation in test scores.

4.2.5 Statistical Analyses

Log transformation and repeated-measures mixed linear modeling using Proc Mixed in the Statistical Analysis System software (Version 8.1, SAS Institute, Cary, NC) provided estimates of percent differences in means (fixed effects) and between- and within-athlete coefficients of variation (CV) (random effects) for each fitness and anthropometric test. Separate analyses were performed for each gender at each level (i.e. State Female, National Female, State Male, and National Male). Within-athlete changes from test to test for years in the program (0.5 – 2.5 y) and phase (early-, middle-, and late-) are reported here, while between-athlete differences for age and calendar year have been reported separately (Chapter 3).

The fixed effects in each analysis were Phase, Year, Year*Year, Age, Age*Age, Time, Time*Time, and Time*Age, where Phase was a nominal within-subject effect with levels of early-, mid-, and late-season (i.e. January-April, May-August, September-December, respectively), Year was a numeric between-subject effect representing the calendar year when each player was recruited (1996 - 2003), Age was a numeric between-subject effect representing the age of the player at recruitment (14 – 19 y), and Time was a numeric within-subject effect representing time (in years) in the program (up to 3.0 y). Quadratic effects for Age, Year, and Time were included in the model as the simplest approach to allow for non-linear effects of these predictors. An additional fixed effect (FirstTrial) was included to adjust out any overall poorer score when athletes were assessed for the first time in the program, though FirstTrial effects are not reported.

The random effects in the analyses were Athlete, Athlete*Season, Athlete* FirstTrial, and the residual, where Athlete was the identity of the athlete (to estimate pure between-athlete variance), Season was a nominal variable representing year in the program (to estimate within-athlete variance between seasons), FirstTrial estimated any additional within-athlete variance in the athlete's first assessment in the program, and the residual estimated within-athlete variance from test to test within a season. Individual responses for phase changes were estimated by multiplying the residual by $\sqrt{2}$, while individual responses for seasonal changes were calculated by multiplying seasonal variation by $\sqrt{2}$ and are expressed as a percent. Individual variation is expressed as standardized effect sizes (ES) calculated from a ratio of variation within an athlete between phases or seasons and the between-athlete variation within a test session.

Inferences have been made about true (population) values of changes in the mean via precision of estimation (using 95% confidence limits and chances that the true change was substantial) rather than via null-hypothesis testing (using p values and statistical significance). For assessment of magnitude, a change in the mean was expressed as a standardized effect size (ES) by dividing by the between-subject standard deviation (SD). The smallest substantial (worthwhile) change was interpreted an ES of 0.2 as [68]. Quantitative evaluation of effect sizes were: <0.2, trivial; 0.2 – 0.59, small; 0.6 to 1.19, moderate; >1.2, large. For the sake of parsimony, only effects that were at least moderate in size (ES >0.2) are reported. Chances of substantial change were estimated with a spreadsheet and interpreted qualitatively as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; 25-75%, possible; >75%, likely; >95%, very likely; >99% almost certain [196, 235]. Effects sizes of 0.6 and 1.2 were interpreted as thresholds for moderate and large effects respectively, as suggested for testing of team-sport athletes [146].

The magnitudes and qualitative descriptors of individual responses were determined using the same method as the magnitudes of the mean estimates.

<u>4.3 Results</u>

4.3.1 Phase Changes

All responses to phase of the year are expressed as group mean changes (Figure 4.1). In general there were positive changes in body size and variable changes in fitness from phase to phase. National males showed an early phase increase in body mass (effect size, 0.24; 95% confidence limits, ±0.09; chance of substantial increase, 75%) and National females showed a similar effect in this time (0.23; ±0.07; 75%). National males also showed an early phase increase in shuttle run (0.54; ±0.34; 98%) and a mid phase increase in vertical jump (0.33; ±0.22; 88%). State females also had an early phase increase in shuttle run (0.28; ±0.14; 87%), though this improvement reversed in the late phase (0.27; ±0.13; 84%). State males had an early phase increase in vertical jump (0.27; ±0.13; 86%) and a mid phase improvement in sprint time (0.37; ±0.16; 98%). Changes in height, skinfolds, and 20-m sprint between phases were trivial for all groups (effect-size range, -0.19 to 0.19).

4.3.2 Years in the Program

All responses to years in the program are expressed as group mean changes (Figure 4.2) and individual responses (Table 4.1). While analysis was conducted in whole and half year increments, for ease of reading, results in Figure 4.2 are presented only in whole years. Substantial changes in fitness generally required extended periods of time in the National female group. Vertical jump only improved after 2 years (small effect size, 0.36; 95% confidence limits, ±0.31; chance of substantial increase, 85%). At least 2.5 years was necessary for substantial improvements in shuttle run (0.42; ±0.42; 85%), skinfolds (0.37; ±0.33; 84%), and body mass (0.27; ±0.17; 79%). In contrast, for the males there were substantial improvements in some tests after just 1 year. National males had shown improvement in shuttle run (0.42; ±0.42; 85%) and body mass (0.38; ±0.16; 99%) by 1 year in the program. By 1.5 years, National males had also shown a substantial increase in height (0.28; ±0.12; 90%) and by 2.0 y had shown improvement in skinfolds (0.40; ±0.47; 80%). National males did, however, show a dramatic decline in shuttle run performance between two and three years in the program (-0.55; ±0.39; 96%). For the entire duration of their time in the program, State females only showed a substantial increase in body mass at 2.0 y (0.26; ±0.16; 78%). By 0.5 y, State males had shown small improvements in vertical jump (0.33; ±0.12; 98%), by 1.0 y had improved sprint time (0.41; ±0.22; 97%) and body mass

(0.39; ±0.08; 100%) and by 1.5 years had improved shuttle run performance (0.28; ±0.24; 75%).

Figure 4.1 – Within season changes in fitness
Group estimates for changes within a year for National Females (●), National Males (○), State Females (▼), and State Males (▽). Error bars represent 95% confidence limits while the filled bar (▮) represents the typical error of measurement for the test and the open bar (▯) represents the combined smallest worthwhile beneficial change for all groups calculated as 0.2 × SD. Group means at each phase are separated slightly for clarity.

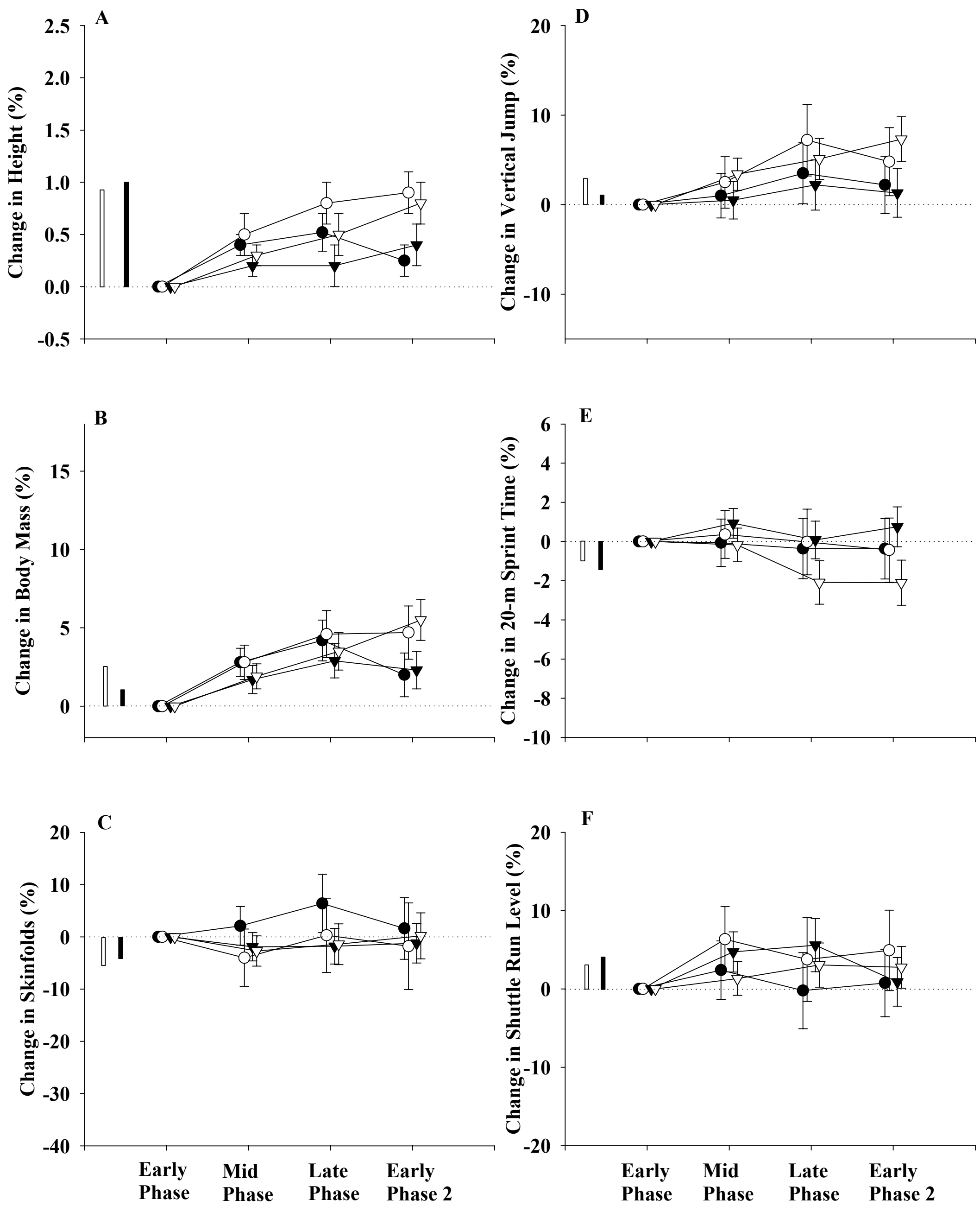
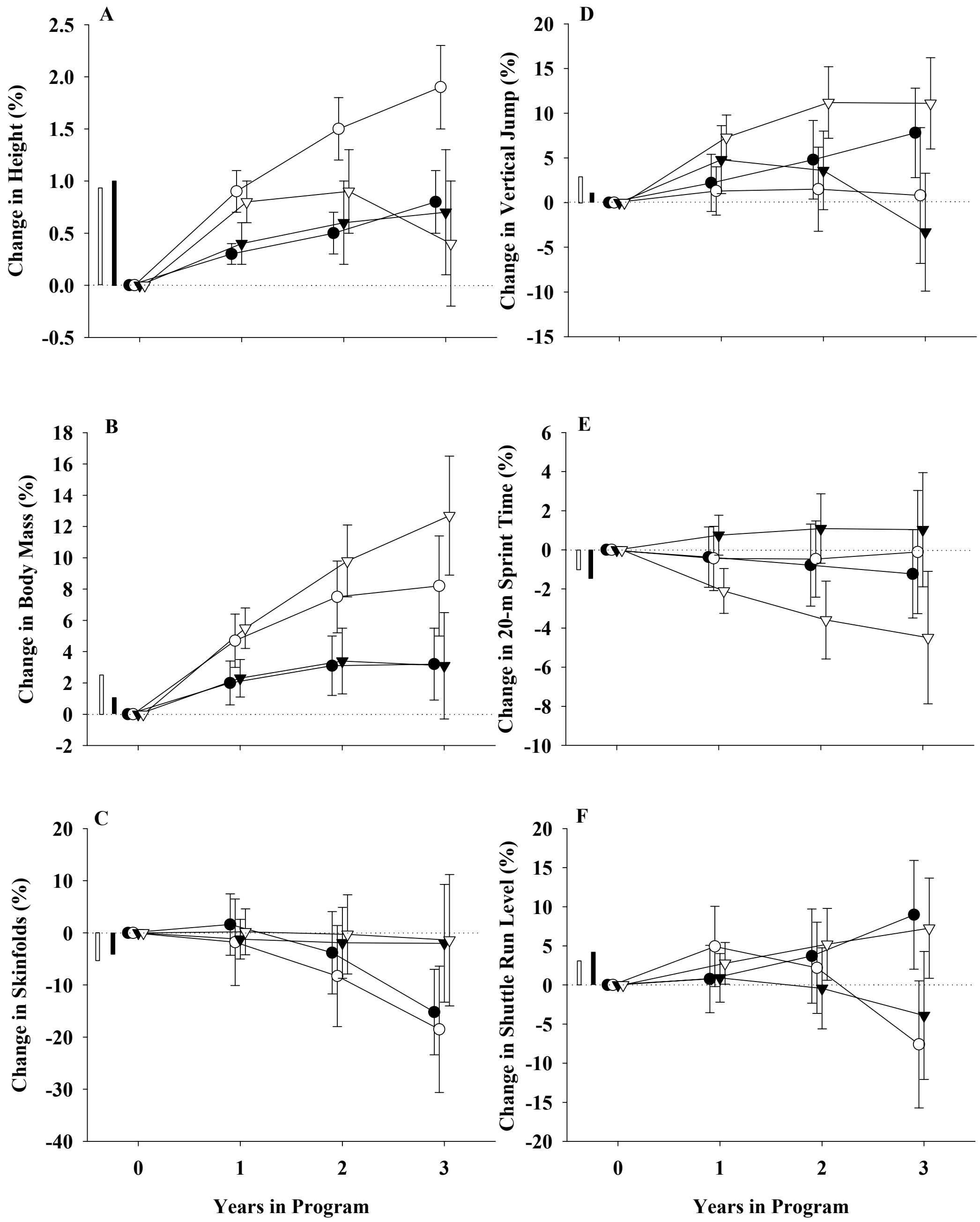


Figure 4.2 – Changes in fitness with years in the program
Group estimates for changes with number of years spent in respective programs for National Females (●), National Males (○), State Females (▼), and State Males (▽). Error bars represent 95% confidence limits while the filled bar (▮) represents the typical error of measurement for the test and the open bar (▯) represents the combined smallest worthwhile beneficial change for all groups calculated as 0.2 × SD. Group means at each season are separated slightly for clarity. Figure 4.2 follows the same y-axis scale as Figure 4.1 to facilitate easier comparison of the magnitude of changes within and between seasons.



4.3.3 Within-Athlete (Individual) Variation

Greater variation in fitness tended to exist in the State level, and male players (Table 4.1). The percent random variation within a season ranged from the smallest variability in National male height (0.34%) to the largest variability in State male skinfolds (15%). Random variation, expressed as magnitudes of the individual variation within a season ranged from small variation in body mass of male and female National players (ES: 0.23) to moderate variation in National male sprint time (ES: 0.87). A similar pattern of variability existed in variability between seasons, with ranges from the smallest variability in National female height (0.44%) to the largest variability in State male skinfolds (20%). Magnitudes of the individual variation between seasons ranged from small variation in body mass of National players (ES: 0.26) to moderate variation in National male sprint time (ES: 1.03). The magnitude of variation of height in all groups both within and between seasons was trivial (ES: 0.09 – 0.13) State players showed greater individual variation between phases and over seasons on all tests by factors (State / National) ranging from 1.05 to 2.44, and males showed greater variation on all tests by factors (Males / Females) ranging from 1.10 to 1.59, except in sprint time. While group effects for phase and season were typically trivial to small, the individual responses were mainly small to moderate in magnitude (Table 4.1).

Table 4.1 - Within-player variations in fitness

Assessment of within-player variation for levels (National vs State) and genders (male vs female). Individual response to phase and season indicates the typical variation in change scores an individual may expect over the given time period. Magnitudes are qualitative descriptors based on Cohen effect sizes calculated from a ratio of variation within an athlete between phases or seasons and the between-athlete variation within a test session.

Test	**Gender**	**Individual Response to Phase (%)**		**Magnitude of Individual Response to Phase**	**Individual Response to Years in Program (%)**		**Magnitude of Individual Response to Years in Program**
		State	**National**		**State**	**National**	
Vertical Jump	F	11	7.0	Moderate	13	7.5	Moderate
	M	8.0	7.2		10	7.3	
Shuttle-run level	F	12	10	Moderate	13	10	Moderate
	M	12	10		13	10	
Skinfolds	F	12	12	Small	19	17	Moderate
	M	15	14		20	17	
20-m sprint time	F	3.3	3.0	Moderate	4.4	3.6	Moderate
	M	4.2	3.0		5.3	3.6	
Mass	F	3.6	2.8	Small	5.2	3.8	Small
	M	3.9	2.8		5.3	3.2	
Height	F	0.47	0.37	Trivial	0.9	0.44	Trivial
	M	0.62	0.34		1.4	0.54	

Individual responses for phase changes were estimated by multiplying the square root of two by the residual, while individual responses for years in the program were calculated by multiplying the square root of two by seasonal variation.

4.3.4 Between-Athlete Variation

Differences in between-subject standard deviations were trivial or small between genders and levels. While details are available elsewhere (Chapter 3), averaged over all players, the standard deviations were: skinfolds, 29%; shuttle run, 14.4%; vertical jump, 13.4%; body mass 12.9%; 20-m sprint time, 4.7%; height 4.5%. Smallest worthwhile changes in the measures were calculated as 0.2 multiplied by the between-athlete variation (i.e. 0.2 × SD) and expressed in Figure 4.1 and Figure 4.2.

4.4 Discussion

This study has documented the magnitude of changes in fitness and anthropometric test scores within and between basketball seasons in a very large cohort of junior male and female players, at different levels of competition. That these athletes were actively training in State and National level training programs allows conclusions to be drawn about the short-tem and long term progress an individual makes while in representative-level basketball training programs. The variability of test scores by gender and level and estimated responses of individual players between phases of a year and over several years have also been quantified. Fitness changes between phases of a year were mostly trivial or small. Changes over longer periods were trivial to moderate in magnitude and tended to occur in the first 18 months of the National programs. Substantial individual variation in the magnitude of changes was observed. The findings of deterioration in some measures of fitness and conditioning in some groups suggest these are priority areas for basketball authorities, team coaches and strength and conditioning practitioners. The lack of substantial improvement within a given training and competition year suggests that players and coaches should take a longer term view of improving fitness over several years. These results provide a framework for coaches and scientists to evaluate the magnitude of observed changes in fitness and anthropometric test scores in young basketball players.

4.4.1 Changes in Fitness from Phase to Phase within a Year

There is general consensus in the basketball community that fitness and conditioning programs must follow a periodization schedule relative to the timing of the competition phase within annual training plan. Most team sports undertake the majority of their fitness training during the pre-season so that upper and lower body power is at its peak during the competition phase, while competition-phase training focuses on individual skills and team-work [49]. However the small number of research studies examining fitness in basketball players do not consistently support the effectiveness of this approach across a range of tests in competing athletes. For example, some studies investigating the effects of pre-season basketball training that involves resistance training show impairment in measures of anaerobic fitness with training [141], others show no substantial change [113] and conversely others show improvement [293]. Similar inconsistencies can be seen in measures in aerobic fitness and anthropometric measures [47, 62, 113, 141, 293]. Since the majority of State players train in year round programs and often compete in several leagues (school, city, and representative programs) at any given time, their opportunity for periodized programs is limited. It is important to recognise that there is little opportunity for players to improve fitness, even at the junior State level, so fundamental movement skills (e.g. sprinting and jumping) and fitness must be developed prior to this level in junior clubs and school physical education and sport programs. Once players reach senior and representative levels, coaches may place such a high emphasis on team and individual skills that little fitness develops in the limited amount of time allocated for physical conditioning in a periodized program.

The adolescent period can involve quite marked changes in stature and body composition. However neither State group showed a substantial change in body mass between any phases, consistent with the majority of the pertinent literature that also demonstrates limited change in body mass between phases of training [47, 62, 141, 293]. The increase in body mass with unchanging skinfolds in National players likely reflects an increase in muscle mass, possibly due to the introduction of players to resistance training programs at the National level. While there may be some question regarding the value of measuring height, body mass, and skinfolds several times per year, these measures are useful for tracking changes in body size and composition, such as muscle mass, that are related to performance [319]. Adding body mass while maintaining or reducing skinfolds can provide useful information on the effectiveness of dietary plans and resistance training interventions typically encountered in higher-level programs.

4.4.2 Longitudinal changes from year to year

For females spending more than 1.5 y in their basketball program, the pattern of changes in fitness test scores are relatively stable during the initial 1.5 y. It is possible that females new to their respective programs typically spend more time on game skills and teamwork fundamentals, so fitness training has traditionally taken a lower priority in the first year. In BA programs, National players usually begin to improve their power and aerobic fitness with greater emphasis on high intensity court-based training and strength and conditioning training in their second year on scholarship, spending their first year developing the necessary foundation skills and fitness to become senior players. The lack of substantial improvement in fitness of State females may reflect growing interests outside of basketball, if players have not progressed to higher levels. A consequence of this pattern is that National coaches are increasingly being presented with players with lower athletic capacities.

In males an opposite pattern was evident to that of the females. National males showed only a small improvement in shuttle run and no substantial changes in sprint time and vertical jump during their time in the National program. In further contrast, State males showed a substantial improvement in vertical jump, sprint time, and shuttle run performance in their initial two years in their program. Since these players had lower initial fitness than National males, there may have been greater potential for improvement in State-level athletes. The dramatic decline in shuttle run performance likely indicates that many National males became complacent about their fitness due to the majority of players playing for extended periods of time in the second-tier semi-professional league without making progress towards professional contracts or American collegiate recruitment. Conversely, State males apparently continued to strive toward the National level by developing their fitness. Such an observation highlights the importance of personal motivation and coaches making fitness development a priority in player development. Without appropriate focus of the player and coach, fitness development can plateau or even reverse.

Changes in aerobic fitness are somewhat different than that which might be expected in children of this age. Expected age related changes in aerobic fitness of females shows a decrease from VO_{2max} of 46 to 41 $ml^{-1}·kg^{-1}·min^{-1}$ between 14 and 17 y [27] or a $\dot{V}O_{2max}$ in absolute terms of 2.3 to 2.1 $l^{-1} \cdot min^{-1}$ between 13 and 18 y [259]. Expected age related changes in aerobic fitness of males shows a decrease from $\dot{V}O_{2max}$ of 54.5 to 51.5 $ml^{-1} \cdot kg^{-1} \cdot min^{-1}$ [27], though $\dot{V}O_2$ slightly increased between 14 and 18 y from of 2.7 to 3.3 $l^{-1} \cdot min^{-1}$ when considering maximal oxygen consumption in absolute terms [259], representing a disproportionate increase in body mass relative to oxygen consumption. Little data exists for longitudinal performance on power out put tests of either male or female children over 14 y though it is widely assumed that both absolute power and power to weight ratio improves as adolescents progresses in males though stabilizes in females at approximately 15 yeas old [258].

Athletic training is unlikely to have a substantial effect on development of height or the onset of puberty [77]. Therefore, the similarities in the magnitude of height and body mass changes between levels of each gender in the current study likely reflect typical adolescent changes rather than those induced by physical training. One study monitoring long term trends in anthropometric measures in basketball players indicated a small to moderate increase in body mass with long periods of time in basketball training, results similar to the current findings [151]. National male and female players showed a decrease in sum of skinfolds with time in the program, in contrast to both State-level groups, who exhibited no substantial change in skinfolds. National players have higher training volumes, greater exposure to advanced resistance training techniques, and professional nutritional advice that State players cannot easily access. These support services, possibly coupled with a greater maturity and commitment to training and nutrition issues, may have contributed to reductions in body fat of the higher level players. The changes in skinfolds took longer to become apparent in females, possibly because entry to respective programs typically occurs in mid to late adolescence (14-17 years). Greater adipose deposits in female athletes regardless of training and nutrition would be expected. After several years in their programs, differences between State- and National-levels became more distinctive, presumably because the differences in the rate of morphological changes associated with the adolescent growth spurt had declined, and more specific conditioning programs started to take effect.

4.4.3 Individual Variation in Fitness

There is an intuitive understanding among basketball coaches that individual variation in fitness and performance exists among players, yet this issue has not been investigated in any previous study. Studies in highly trained swimmers show a greater variation for an individual's performance from competition to competition than younger swimmers competing at the sub elite level [287, 300]. There is also a similar result with substantial individual variation in the improvements of fitness of basketball players. Not surprising, the higher level National players had less variability in all anthropometric and court tests. One explanation for this finding is that athletes at higher levels of the game with a greater level of fitness will have less of a response to fitness training [14, 134, 211]. Less variability could also be attributable to the highly structured, year-round training program of the National-level players. Additionally, inconsistent performances from players would not be rated favourably by coaches, so players with high variability may simply not be selected for national teams.

The variability in anthropometric and fitness test scores is particularly important when interpreting the magnitude of change from test to test. The variation for any individual player from test to test is represented quantitatively as the sum of the overall mean effect for the group (Figures 4.1 and 4.2) and a random effect for individual variation (Table 4.1). For example, the mean estimate of the change of State male vertical jump during the early- to mid phases is 3.4% (Figure 4.2), while the random effect of individual response to phase can add or remove 5.7% (Table 4.1). Therefore, between the early and mid phases, the change in vertical jump of an individual State male is typically between –2% and +9%. In practice the coach can be reassured the mean change is 3.4% improvement in vertical jump, but given the individual variation in response to training some players will improve by as much as 9% while others may actually lose up to 2% over the same period. The same interpretation is applied to changes from year to year. This quantitative approach involving consideration of both mean effects and individual responses to training gives a clearer indication of the overall pattern of changes in fitness measures across a team of junior basketball players. Clearly, the effect of individual responses becomes particularly relevant when group effects are trivial or small. Therefore, while the main (group) effect for a given fitness score may be a small and positive, the variability in an individual player's response may range from a small decrease to a moderate or large improvement. Clearly coaches should consider the individual fitness needs of different players within the overall team program.

Quantifying random variation serves other purposes in addition to estimating individual responses. The random variation between two tests conducted several days apart helps determine if observed changes are greater in magnitude than the simple typical error of measurement of the test. If the observed change is greater then the error of the test then the change can be considered 'real' rather than simply noise or error of measurement [147]. The TEM of a test is a valuable tool in assessing the reliability of a test as it expresses the expected magnitude of variation within each subject. Sports science staff have the responsibility of ensuring that the TEM has been established and reported for every anthropometric and fitness test administered in junior and senior sporting programs.

4.5 Conclusion

In the current study, the magnitude of changes in anthropometry and fitness for players from phase to phase within a season and from season to season were analysed. Typical responses to phase changes and over multiple seasons were trivial to small in magnitude. However the individual responses were typically small to moderate highlighting the need for assessment and training prescription to be considered on an individual basis. The small number of short-term changes with different phases of the year appears to reflect the nearly continuous competition schedules of high school players. The higher variation in test scores of younger athletes is likely related to a higher potential for improvement, while older athletes have a greater familiarity with the testing protocols. Basketball coaches should continue to emphasize fitness in development-level programs, but a greater focus in more senior level programs is suggested to maintain and improve fitness. Assessing both the mean effects and individual response to training is warranted for tracking changes in individual players within a season and over consecutive years.

CHAPTER 5: VALIDATION OF AN OPTICAL ENCODER DURING FREE WEIGHT RESISTANCE MOVEMENTS AND ANALYSIS OF BENCH PRESS STICKING POINT POWER DURING FATIGUE

5.1 Introduction

For at least three decades researchers have been aware of the need for a high degree of specificity between the power output at which a subject trains and the power output at which the subject is tested [70]. Until recently, detailed analysis of power output during free-weight training has only been possible by using video or videographic analysis to derive velocity by measuring distance and time [56, 149]. Video analysis is a very labour and resource intensive method of analysis, limiting its utility as a research or practical tool for large scale power output data assessment collected over extended periods of time.

To overcome the labour intensive nature of video analysis in resistance training research, the testing and training of subjects is usually performed with isokinetic or isometric protocols [31, 102]. However, deriving practical recommendations for athletic training from this approach centers on resolving concerns of different recruitment patterns and mechanisms of fatigue inherent in different forms of contractions [73, 170]. The findings from these laboratory training protocols may not directly apply to athletes across a range of sports. Research intended to apply to athletes should ideally be conducted initially in the laboratory setting [31] and then transferred to the free-weight setting [161]. Unfortunately the degree of experimental control in the field often does not match that achieved in the laboratory. Even when research training programs employing free-weights attempt to control for training volume or intensity between training groups, there can be substantial differences between groups in total work performed, power output, or time under tension [71]. Therefore, an accurate method of monitoring long-term free-weight resistance training programs is essential to the application of resistance training research in an applied setting. From the perspective of a resistance training coach or athlete, immediate feedback of results is important for improving lifting performance, as is long-term tracking of detailed performance analysis [232].

A number of well controlled research studies have assessed the kinetic analysis of the bench press, a very common free-weight resistance training lift [95, 224, 318]. Changes in bench press movement kinetics have been typically assessed by increasing the intensity of single repetitions [95, 318]. However, there is no analysis of how movement kinetics change as fatigue accumulates over a training set that consists of multiple sets and repetitions, typical of most resistance training programs [249]. Of particular interest is assessing changes in both overall power production during the full concentric movement, and in power production in each of the discrete phases of the concentric bench press movement [95, 318]. Since both fatigue [254] and movement kinetics [233] play determining roles in training outcomes, it is relevant for scientists to evaluate, and resistance training coaches to monitor, the changes that occur in movement kinetics as a result of fatigue.

The potential application of optical encoder technology in various training and research settings has spurred the development and release of several commercial devices. Recent research has utilized linear position transducers to measure power of movements such as bench press [192], lunge [74], bicep curl [157] and vertical jump

[72, 157]. While there is a large potential for these devices to improve the quality and control of resistance training research, limited data exist on their validity to measure power. To date only one study has validated this type of instrumentation against a criterion measure [74]. Cronin et al. [74] validated the Unimeasure™ optical encoder using a force plate to measure force output during ballistic jumping, but only measured ballistic movements on force-related properties, not power. The purpose of the current research was therefore twofold. First, this study set out to evaluate the validity of the Gymaware™ linear position transducer to measure a variety of movement kinematics of the bench press and squat movements. Secondly, this thesis chapter sought to investigate changes in power output that occur over a typical, fatiguing bench press training session in highly trained junior basketball players.

5.2 Methods

5.2.1 Approach to the Problem

To assess the validity of the Gymaware™ optical encoder to measure power, both concentric and eccentric mean and peak power output were assessed of 12 subjects while they performed Smith Machine back squats, Smith Machine bench press throw, and free-weight bench press, each on separate days. Each lift was simultaneously recorded using a video camera and an optical encoder. Video captures were later analyzed for time and position data from which power was calculated. Validity was evaluated using established statistical procedures. Validity of the optical encoder compared to video analysis was evaluated from the magnitudes of standard errors of the estimate (SEE) and coefficients of variation (CV). Relationships between the criterion (video) and optical encoders were quantified using Pearson Product Moment and expressed as an r value.

To investigate changes in power output that occur over a typical bench press training session, seven subjects performed four sets of six of bench press repetitions, while being continuously monitored using an optic encoder. Data collected from the optical encoder was then exported and peak power of the initial acceleration (i.e. first phase) and maximal strength (i.e. third phase) [95] for each repetition was quantified. Since the sticking point represents a phase of declining power, the current analysis inspected the lowest power between the first and third phases. Since the fourth phase of the bench press represents another phase of declining power that inevitably ends in the bar stopping at the end of the concentric phase, no power analysis was conducted on this phase. Power changes in each phase were then analysed to quantify power changes over the 24 total repetitions in each phase relative to the first repetition.

5.2.2 Subjects

The sample group comprised 12 highly trained junior male basketball players (age 17.9 ± 0.6 y, height 198.4 ± 9.8 cm, body mass 97.5 ± 16.5 kg; 3RM squat 105.0 ± 13.8 kg; 3RM bench press 80.5 ± 8.4 kg, mean ± SD). All subjects had moderate to extensive weight training experience ranging from six months to beyond two years, including bench press and squat exercises. Subjects provided written informed consent for testing, data collection, and publication of results as part of their Scholarship Agreement with the Australian Institute of Sport (AIS), in accordance with requirements of the AIS Ethics Committee. Testing and training procedures were explained before the start of the study and subjects were informed that they could withdraw from testing at any time without prejudice.

5.2.3 Procedures

5.2.3.1 Lifts Evaluated

Subjects were evaluated performing a single repetition of their 3RM (~94% 1RM, [54]) on a free-weight bench press, a Smith Machine back squat, and a 40 kg Smith Machine bench press throw, each on separate days. Data for each lift were simultaneously collected using an optical encoder and digital video. For the bench press, subjects completed a warm up involving 10 min of stationary cycling and three sets of bench press comprising 12 repetitions at 20 kg, 6 repetitions at 30 kg, and 3 repetitions at 40 kg with 1 min rest between sets. Bench press repetitions were then evaluated according to established criteria [89]. Briefly, athletes lowered the bar until the chest was touched lightly approximately 3 cm superior to the xiphoid process. The elbows were extended equally with the head, hips, and feet remaining in contact with the bench throughout the lift. Previously documented 3RM test records were used as a guide for selecting the resistance.

For the Smith Machine back squats, subjects completed a warm up involving 10 min of stationary cycling and three sets of back squats comprising 8 repetitions at 40 kg, 6 repetitions at 60 kg, and 3 repetitions at 70 kg with 1 min rest between sets. Squats were also evaluated according to established criteria [89]. Briefly, subjects supported the bar above the posterior deltoids at the base of the neck. Athletes slowly flexed the knees and hips, lowering the bar until the front of the thighs were parallel with the ground. Heels of the feet remained flat on the ground while the back remained flat and the head level to keep the force on knee and hip flexion and extension. Previously documented 3RM test records were used as a guide to select the resistance.

On a separate day to the bench press and squat testing, subjects were evaluated for maximal power output during a 40 kg Smith Machine bench press throw. Prior to testing each subject completed a thorough warm-up involving 10 min of stationary cycling and three sets of bench press comprising 12 repetitions at 20 kg, 6 repetitions at 30 kg, and 3 repetitions at 40 kg with 1 min rest between sets. Subjects then performed two individual 40kg bench press throws, separated by at least one minute [21]. Athletes lowered the bar until the chest was touched lightly approximately 3 cm superior to the xiphoid process. The elbows were extended equally with the head, hips, and feet remaining in contact with the bench throughout the throw. The subject held the bar on the chest for 2 s before ballistically throwing the bar as high as possible. The bar was then caught by the subject with no assistance from the experimenter or any kind of gradual mechanical breaking system of the Smith Machine, though safety braces were in place approximately 3 cm superior to the xiphoid process should the subject fail to catch the bar.

5.2.3.2 Optical Encoder

The displacement and time between data points of each bench press and squat repetition was measured with a Gymaware™ optical encoder (Kinetic Performance Technology, Canberra, Australia). This device consists of a spring powered retractable cord which passes around a pulley mechanically coupled to an optical encoder (Figure 5.1), and the end of the cord attaching to the barbell. The unit was positioned on the floor perpendicular to the movement of the barbell. The device measured velocity and distance of the barbell from the spinning movement of the pulley while mass was entered via a personal digital assistant (PDA, Model:

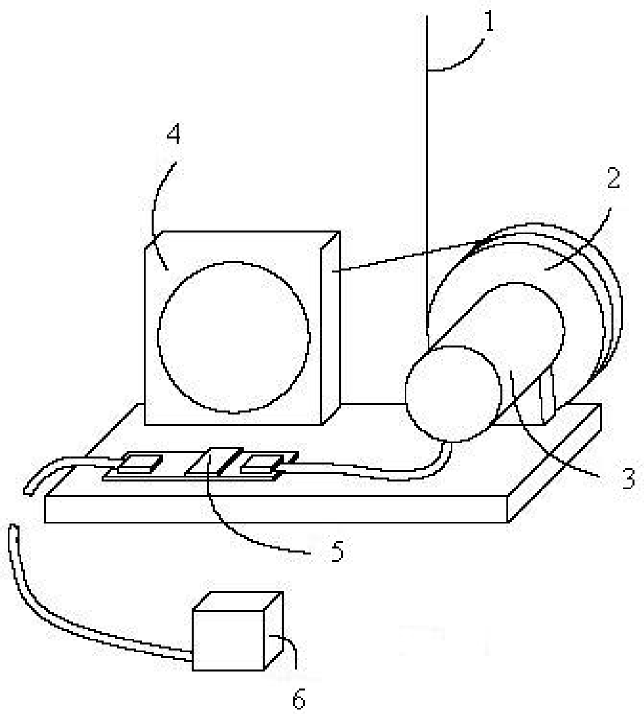
Tungsten-e, Palm, Milpitas, CA) into the device. The device gave one pulse approximately every 3 mm of load displacement with each displacement value time-stamped with a 1 ms resolution. Position - time data points were generated at a maximum rate of 25 Hz. The entire displacement (mm) and time (ms) for the movement were used to calculate mean values for power (see calculations 1 through 7).

5.2.3.3 Digital Video Recording

A digital video camera (Sony – Digital Video Recorder DRC-TRV900E PAL) was used to film each lift for each subject at 50Hz. The camera was placed perpendicular to the front of the bar to record the vertical aspect of the movement. The camera was placed at a horizontal distance of 8 m from the bar to minimize the parallax effect. A reflective marker was placed at the same point as the attachment point of the optical encoder on the bar to digitally track the movements of the bar. A second reflective marker was placed on the lifting apparatus frame to establish a stable point of reference. An image of the lifting apparatus with a vertical calibration pole marked in 0.10 m increments was captured before the start of each testing session. The vertical calibration pole established a distance scale to quantify the vertical displacement of the bar against but does not represent the sensitivity of the measurement.

Figure 5.1 - Gymaware™ optical encoder hardware

Number 1 indicates the retractor cord that attaches to the external load. Number 2 shows the pulley around which the retractor cord wraps. Number 3 indicates the optical encoder that sends a pulse to the microprocessor every 3 mm of rotation. Number 4 shows the retractable cable assembly that stores the retractor cord when the device is in the retracted position. Number 5 indicates the microprocessor and interface circuit that translates pulse information into position and velocity data. Number 6 indicates the infra-red transceiver that communicates with the personal digital assistant (PDA) to store data.



Time and position data were generated with Ariel Performance Analysis System (APAS) motion analysis software (Ariel Dynamics, Inc. Trabuco Canyon, CA) [289]. The vertical calibration poles that provided scale for the frame size were digitized every 0.2m vertically either side of the capture volume. The reflective marker was then digitised using the APAS ‘auto-digitize’ function. The data was unfiltered. Every second frame of data was analysed, resulting in a 25 Hz capture rate in order to compare more closely with the optical encoder time-event encoder sample rate of approximately 25 Hz.

External power was calculated from Gymaware and video time-position data separately through several stages, thus introducing the possibility of slight errors to occur with each step. First, displacement was calculated as the change in position in the vertical plane (1):

$$d = \Delta p \qquad (1)$$

where d is displacement, p is position (m).

Velocity was then calculated as displacement over change in time (2):

$$v = \Delta d / \Delta t \qquad (2)$$

where v is velocity ($m.s^{-1}$) and t is time (s).

Interpolation was used to shift velocity to match the existing time code. To interpolate velocity, the time that the known velocities occurred was calculated (3):

$$t_{vn} = (t_{n-1} + t_n)/2 \text{ and } t_{vn+1} = (t_n + t_{n+1})/2 \qquad (3)$$

where t_{vn} is the time at velocity and n is the frame number.

The gradient of two known consecutive velocities was then calculated (4):

$$a_n = (v_{n+1} - v_n)/(t_{vn+1} - t_{vn}) \quad (4)$$

where a_n is the gradient of the two velocities ($m.s^{-2}$).

Velocity at t_n was then calculated by adding v_n to the product a_n and t_{vn} (5):

$$v_{tn} = v_n + (a_n t_{vn}) \quad (5)$$

Interpolation was also used to match acceleration to the same time code as velocity in the above fashion. Force was then calculated as the product of mass (of the bar) and acceleration (of the bar and gravity) (6):

$$F = m\,(a_{gravity} + a_{bar}) \quad (6)$$

where F is force (N), m is mass (kg), $a_{gravity}$ is acceleration due to gravity ($m.s^{-2}$), and a_{bar} is the acceleration of the bar ($m.s^{-2}$).

Power was then calculated as the product of force and velocity (7):

$$P = Fv \quad (7)$$

where P is power (W), F is force (N), and v is velocity ($m.s^{-1}$).

5.2.3.4 Training Session

The training session involved seven subjects undertaking four sets of six bench presses, with each set commencing every 8 min and 45 s, at intensities of 85, 90, 95, and 95% of the individual's 6RM, in sets one to four, respectively. All repetitions were recorded on the PDA for analysis of changes in kinetics over the training protocol. Files were exported from the Gymaware software and visually inspected for changes within each of the four phases of the bench press as identified by Elliot et al [95]. Mean concentric power for each complete repetition was also analyzed for changes over the course of the training session. Loads of greater than 85% were presumably performed with near maximal effort.

5.2.4 Statistical Analyses

Only the validity of the concentric peak and mean power was analysed for the Smith Machine bench press throw, while the validity of both the concentric and eccentric power was assessed for the free-weight bench press and Smith Machine back squat. Differences between the two methods of measurement (optical encoder and digital video) are expressed as a standard error of the estimate (SEE) and coefficient of variation (CV). Correlations between the two scores were calculated using Pearson Product Moment and expressed as an r value [145]. For each lift, mean differences between measures collected from the optical encoder and power calculated from the video analysis were determined and expressed with 95% confidence limits (95%CL) to establish the precision of the estimate.

The practical significance of differences between criterion and practical measures was based on the smallest worthwhile difference with a small standardized (Cohen) effect size (>0.2), derived by dividing the mean difference by the between-subject standard deviation (SD) [68]. Chances of a substantial true difference were estimated with a spreadsheet and interpreted qualitatively as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; 25-75%, possible; >75%, likely; >95%, very likely; >99% almost certain [148, 196, 235]. Effects sizes of 0.6 and 1.2 were interpreted as thresholds for moderate and large effects respectively, as suggested for testing of team-sport athletes [146].

In order to investigate the changes that occur in bench press power over the single training session, data exported from the Gymaware software were visually inspected for areas of increasing and decreasing power. Once these areas were identified, peak power was identified as the point of highest power within that region. Since the accumulating effect of fatigue over the entire training session was of interest, the first repetition of the first set was used as the point of reference to evaluate changes that occurred in all subsequent repetitions. Power of each phase of the concentric movement (i.e. first, second, and third) were compared between the first repetition with subsequent repetitions (i.e. 2 to 24) to investigate changes in power over the entire training session. Comparisons were also made between the first repetition of each set (i.e. 1, 7, 13, and 19) and subsequent repetitions within that set to investigate within-set changes in power. Finally, mean power of the entire concentric phase of each repetition was also assessed over the training set and within each set. Comparisons were made using a two-way ANOVA with repeated measures and Tukey HSD post hoc analysis. Significance was accepted at $p<0.05$.

5.3 Results

5.3.1 Validity

The validity of power measurements using the optical encoders for the specific free-weight movements expressed with 95% confidence limits are shown in Table 5.1. The SEE for all movements, expressed as a CV, were ≤3.0% and ranged from 3.6 to 14.4 W in absolute terms. The r-value derived from the correlation analysis between the optical encoder and video analysis were ≥0.97 for all measures of power on all lifts ($p<0.01$). There is almost no probability that true differences between the criterion and practical measures are likely to be meaningful in performance research (Table 5.1). Of the ten measurements evaluated, the only measure that showed a difference that was practically meaningful was the peak eccentric bench press power.

Table 5.1 - Validity of Gymaware™ optical encoder power calculation compared with video (criterion measure) power calculations.

Movement	Absolute Power (W, mean±SD)	Standard error of estimate			Coefficient of Variation			Pearson r[b]	Probability (%) of difference being clinically meaningful[c]
		Absolute (W)	Lower[a]	Upper[a]	%	Lower[a]	Upper[a]		
Squat mean eccentric	334 (±116)	3.6	2.3	7.9	1.16	0.75	2.57	1.00	0, almost certainly not
Squat mean concentric	372 (±111)	4.1	2.6	8.9	1.08	0.70	2.38	1.00	0, almost certainly not
Squat peak eccentric	607 (±228)	11.2	7.2	24.6	1.43	0.92	3.15	1.00	0, almost certainly not
Squat peak concentric	755 (±271)	14.4	9.3	31.7	2.16	1.39	4.75	1.00	0, almost certainly not
Throw mean concentric	368 (±43)	10.8	7.3	20.6	2.78	1.88	5.33	0.97	0, almost certainly not
Throw max concentric	727 (±128)	14.0	10.0	23.9	1.85	1.33	3.17	0.99	0, almost certainly not
Bench mean eccentric	328 (±68)	7.1	3.2	11.2	2.27	1.50	4.62	0.99	1, very unlikely
Bench mean concentric	253 (±38)	3.7	2.4	8.1	1.50	0.97	3.30	1.00	1, very unlikely
Bench peak eccentric	553 (±125)	7.8	5.2	15.9	1.33	0.88	2.70	1.00	32, possibly
Bench peak concentric	435 (±119)	13.2	8.7	26.9	3.02	2.00	6.16	0.99	0, almost certainly not

[a]*Lower and Upper refer to lower and upper confidence limits for the mean estimate of the SEE and CV*

[b]*All Pearson r p-values <0.01*

[c]Thresholds for assigning qualitative terms to chances of substantial effects were as follows: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; >50%, possibly; >75%, likely; >95%, very likely; >99% almost certain.

5.3.2 Training Session

5.3.2.1 Typical Examples

The different phases of the bench press are illustrated graphically in a typical example shown in Figures 5.2 and 5.3. Figure 5.2 illustrates a single repetition of a subject at 95% 6RM prior to beginning the training session. Figure 5.3 illustrates a single repetition of the same subject lifting 95% 6RM after the exhaustive training session. Both figures show an initial rise and fall in power prior to the eccentric portion of the bench press movement. This profile indicates the barbell is moving from its resting position in the bench rack into the ready position. Next, there is an increase in power, indicating the eccentric movement of the lift. The power then decreases before increasing again corresponding with the bar reaching the subject's chest and beginning of the concentric movement of the lift. During the concentric movement, power shows an initial spike (first phase) before decreasing into the sticking point (second phase). The subject has pressed through the sticking point when power begins increasing again to the repetition's peak power (third phase). Finally power begins decreasing again to finish the concentric phase (fourth phase). The erratic power after the forth phase represents the subject's placing of the barbell back into its resting position. Once the exhaustive training session was completed (Figure 5.3), there is much lower power in the second and third phases, and the second phase becomes longer.

Figure 5.2 - Typical output from the Gymaware™ software (Example 1)

This example represents free-weight bench press repetition illustrating power output (W) during a repetition in an unfatigued subject. Phases of the bench press are labelled as 1st for the initial portion of the concentric phase, 2nd as the 'sticking point', 3rd as the second high power region, and 4th as the area of deceleration as the concentric phase ends.

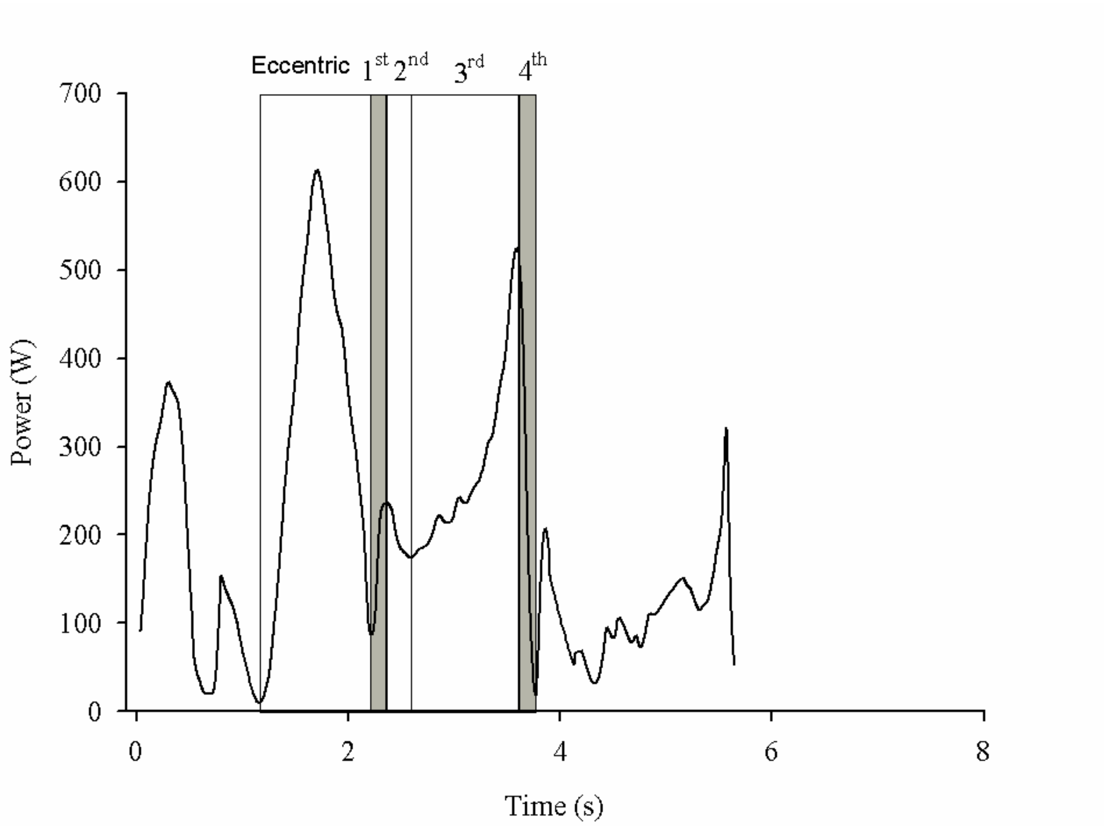
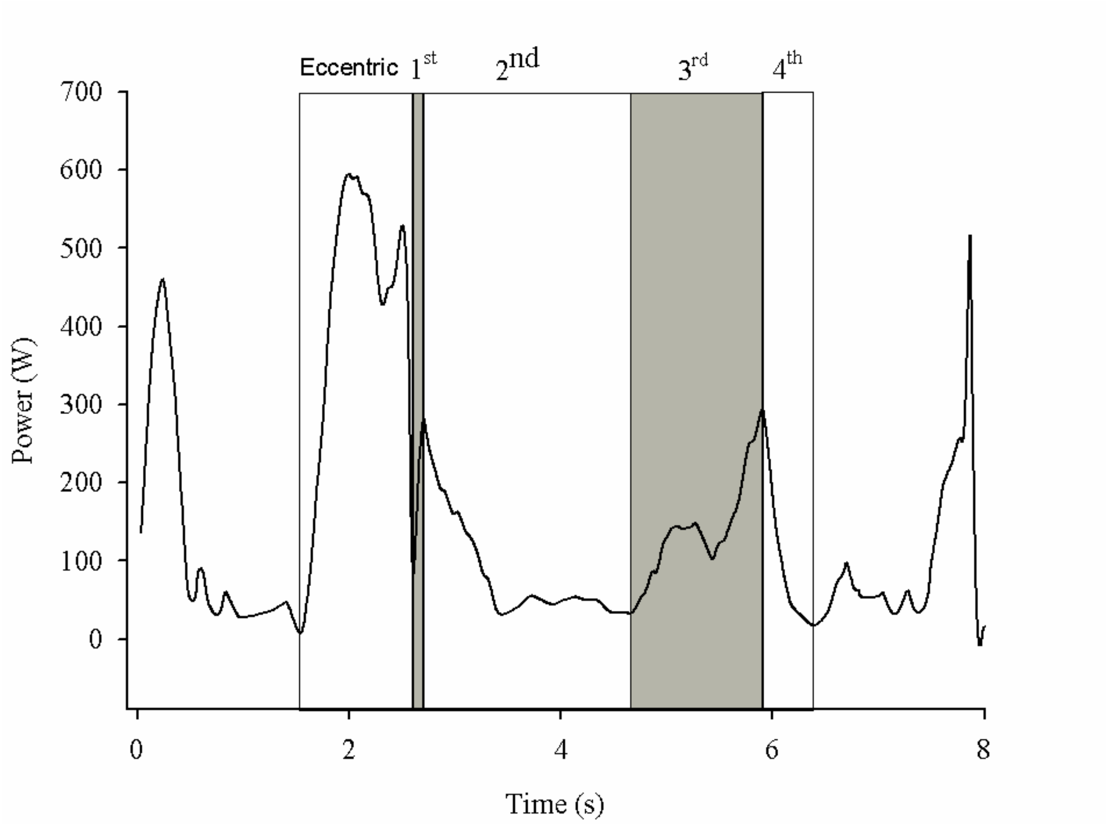


Figure 5.3 – Typical output from the Gymaware™ software (Example 2)

This example represents free-weight bench press repetition illustrating power output (W) during a repetition in a highly fatigued subject. Phases of the bench press are labelled as 1st for the initial portion of the concentric phase, 2nd as the 'sticking point', 3rd as the second high power region, and 4th as the area of deceleration as the concentric phase ends.

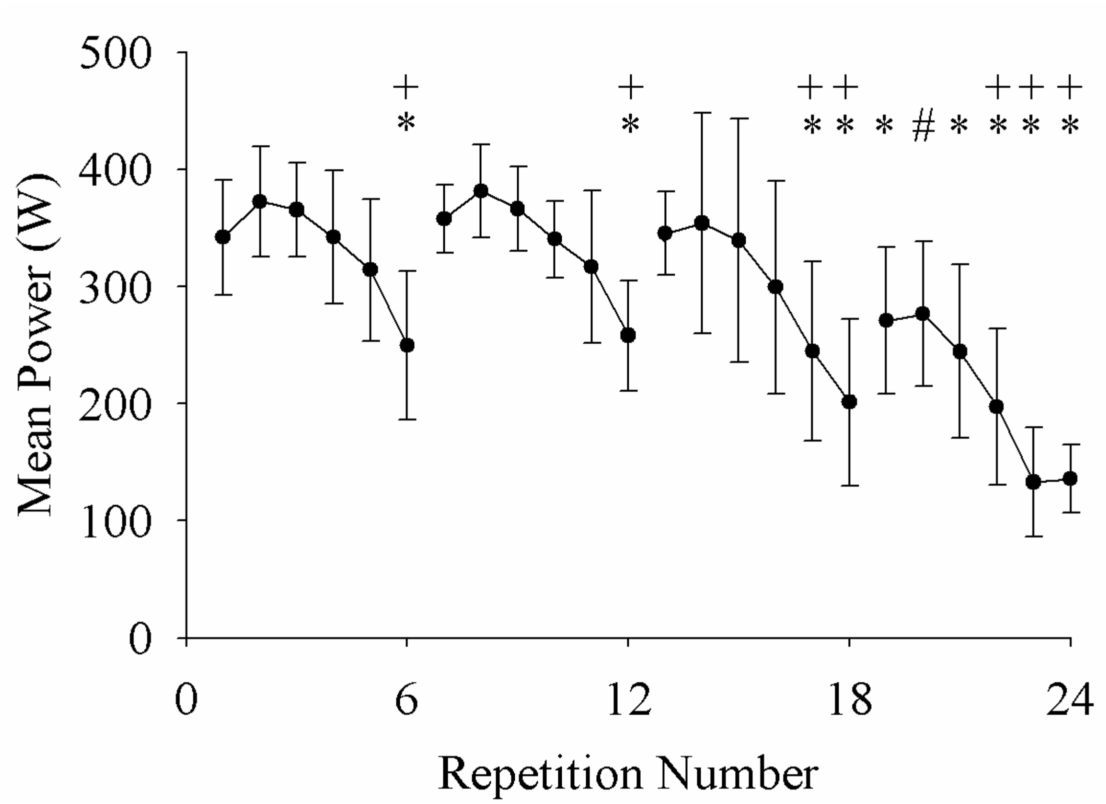


5.3.2.2 Mean power per repetition (Phases 1-4)

When compared to repetition 1, mean power for each concentric movement (Phases 1-4 inclusive) had decreased significantly by repetition 6 (-27%, $p<0.01$), 12 (-24%, $p<0.01$), and 17 to 24 (-19 to -61%, $p<0.03$) (Figure 5.4). Power decrements were also significant within each set at repetition 6 in set 1 (-27%, $p<0.01$), repetition 6 in set 2 (-28%, $p<0.01$), repetition 5 and 6 of set 3 (-29 and -42%, $p<0.01$), and repetitions 4 to 6 of set 4 (-27 to -51%, $p<0.01$) (Figure 5.4). Clearly the decrement in power was evident earlier within the set of 6 repetitions as the session progressed.

Figure 5.4 – Mean bench press power

Kinetic analysis of mean power ± SD (n=12) of the full concentric movement of the bench press (Phase 1-4) over 24 total repetitions divided into four sets of six repetitions. * and # = mean power lower than repetition 1 (p<0.01 and p<0.03 respectively); + = lower mean power than the first repetition within that set (p<0.01).

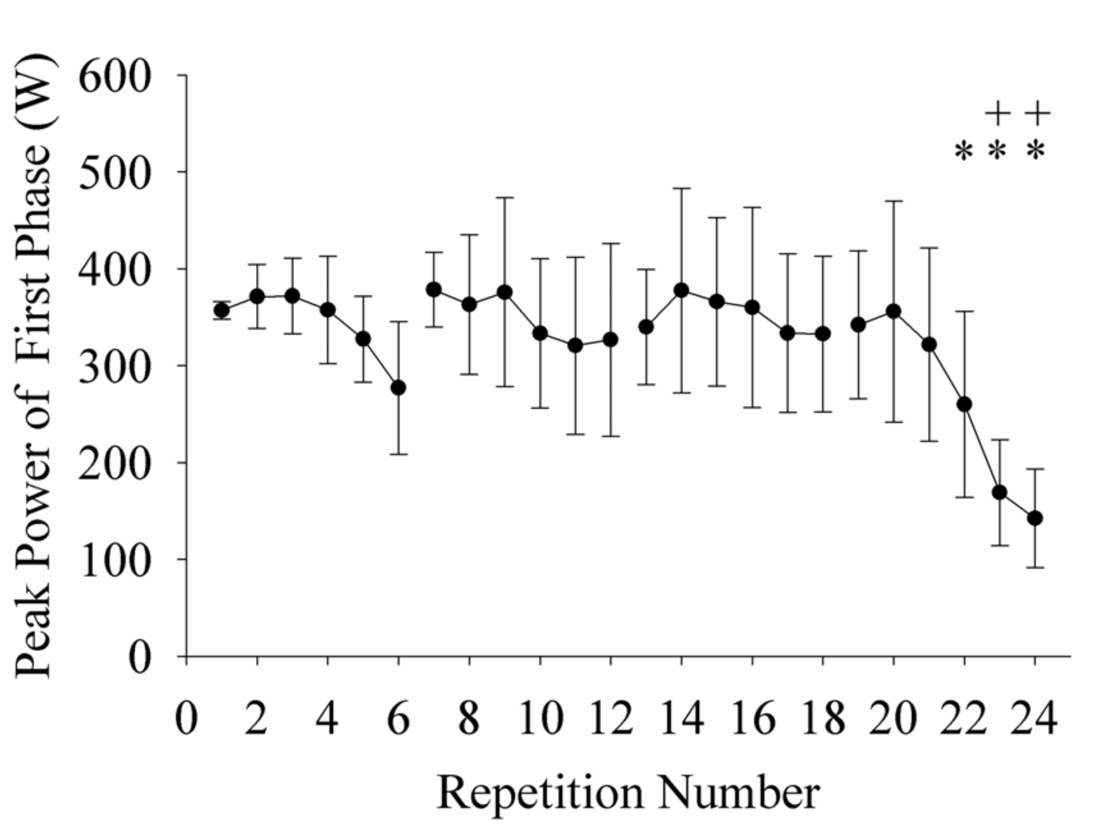


5.3.2.3 Peak power – first phase

In each bench press repetition there was an identifiable initial phase in which power peaked quickly as the subject pressed the bar off their chest (Figure 5.2 & 5.3). Peak power exerted during the first phase was only lower than repetition 1 at repetitions 22, 23 and 24 (-27, -52 and -60%, all p≤ 0.01) (Figure 5.5). There were also within set reductions in power at repetitions 5 and 6 of set 4 (-50 and -58%, both p<0.01).

Figure 5.5 – Peak power of first phase

Kinetic analysis of peak power ± SD (n=12) exerted during the first phase of the concentric movement of the bench press over 24 total repetitions divided into four sets of six repetitions. * = mean power lower than repetition 1 ($p \leq 0.01$); + = lower mean power than the first repetition within that set ($p<0.01$).

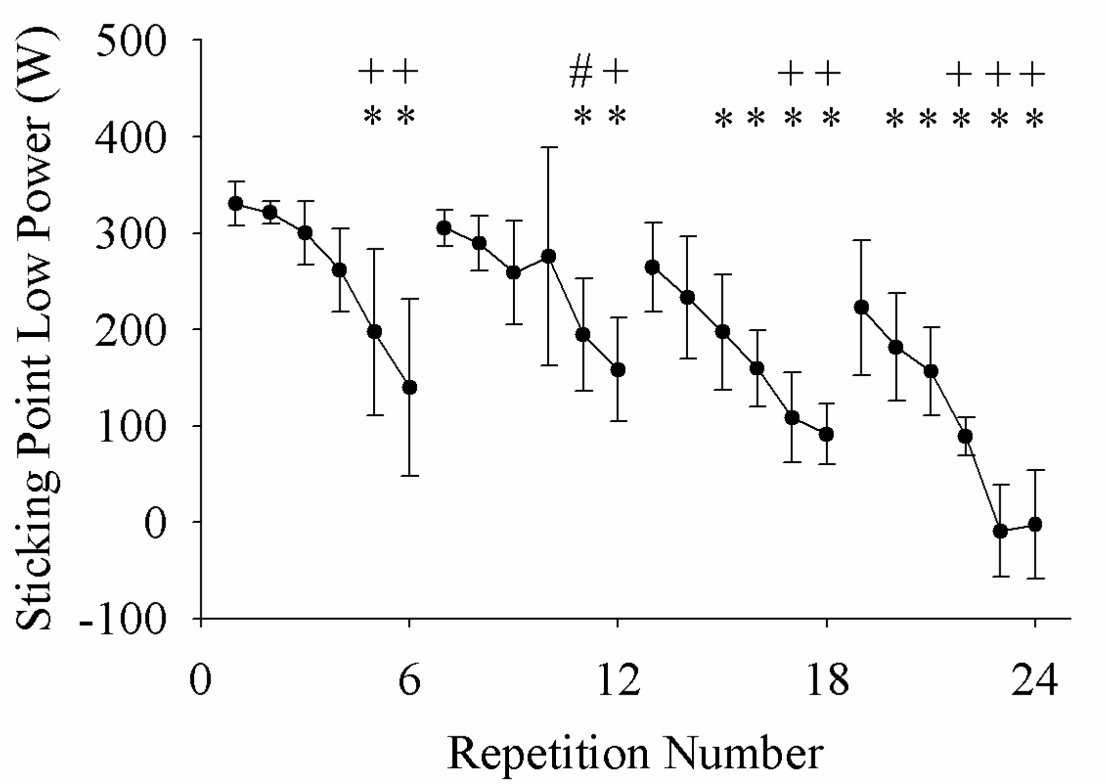


5.3.2.4 Low power – second ('sticking point') phase

The next phase of the bench press, the so-called sticking point, was characterized by declining power after the initial power spike (Figure 5.2 & 5.3). The lowest power measured during the sticking point was lower than that of repetition 1 in repetitions 5 and 6 (-40 and -58%), 11 and 12 (41 and 52%), 15 to 18 (-40 to -72%), and 20 to 24 (45 – 100%, all $p<0.01$, Figure 5.6). Within-set decrements were also observed in repetitions 5 and 6 of set 1 (-40 and -58%, $p<0.01$), 5 and 6 of set 2 (-36 and -48%, $p<0.04$ and $p<0.01$ respectively), 5 and 6 of set 3 (-59 and -66%, $p<0.01$), and 4 to 6 of set 4 (-60 to -100%, $p<0.01$).

Figure 5.6 – Sticking point low power

Kinetic analysis of lowest power ± SD (n=12) exerted during the second ('sticking point') phase of the bench press over 24 total repetitions divided into four sets of six repetitions. * = mean power lower than repetition 1 (p<0.01); + and # = lower mean power than the first repetition within that set (p<0.01 and p<0.04 respectively).

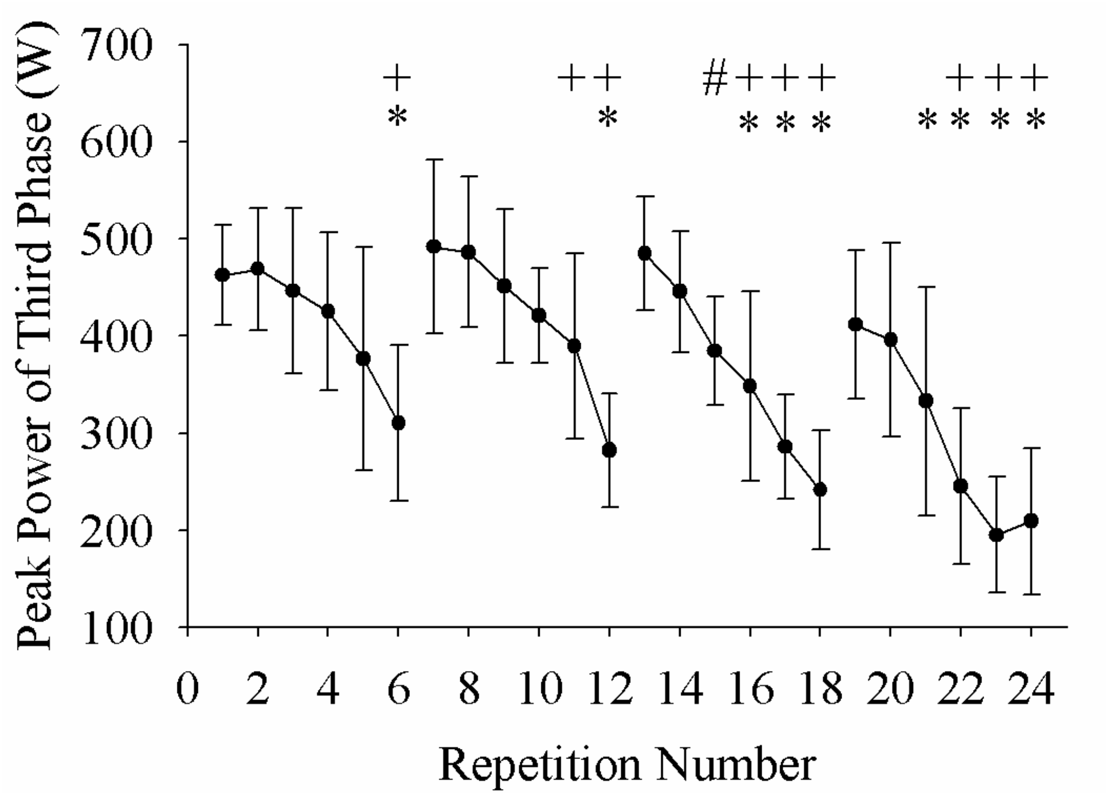


5.3.2.5 Peak power – third phase

After the sticking point was overcome, there was a third phase of secondary high power (Figures 5.2 & 5.3). There was a significant decrease in peak power during the third phase from repetition 1 to repetitions 6 (-33%, p<0.01), 12 (-39%, p<0.01), 16 to 18 (-25 to -48%, p<0.01), and 21 to 24 (-28% to -58%, p<0.01, Figure 5.7). There were also substantial decrements in power at repetitions 6 of set 1 (-33%, p<0.01), 5 and 6 of set 2 (-21 and -43%, p<0.01), 3 to 6 of set 3 (-21 to -50%, p<0.02), and 4 to 6 of set 4 (-40 to -53%, p<0.01).

Figure 5.7 – Peak power of third phase

Kinetic analysis of peak power ± SD (n=12) exerted during the third phase of the concentric movement of the bench press over 24 total repetitions divided into four sets of six repetitions. * = mean power lower than repetition 1 ($p<0.01$); + and # = lower mean power than the first repetition within that set ($p<0.01$ and $p<0.02$ respectively).



5.4 Discussion

The first major conclusion of the study is that the use of the Gymaware™ optical encoder is a valid method of collecting kinetic data on resistance training movements, based on the low CV and SEE derived from the video (criterion) and optical encoder. The second important finding was the decline in mean power over the full concentric movement and decline in peak power at each of the concentric phases, during a high-intensity bench press single training session. The initial phase of the concentric movement was relatively fatigue resistant compared to the second and third phases, illustrated by the peak power output during the sticking point of the bench press not approaching zero until after there was a significant drop in power in the first phase. These data suggest a direct link between the decline in initial production of power with fatigue and the subsequent ability to breech the sticking point in the standard bench press. Due to the widely accepted knowledge of the ‘sticking point’ [95], this finding was not unexpected, though had not been empirically investigated over multiple repetitions of bench press.

5.4.1 Validity of the optical encoder in measurements of power

The study has demonstrated that use of optical encoders is a valid method of evaluating both peak and mean power in a variety of resistance training movements, with a low CV of 1-3% and high r-values of 0.97 to 1.00 for nine out of the ten measurements evaluated. The only variable that showed a substantial practical difference between the optical encoder and video-derived power calculations was the peak eccentric bench press power. This difference in eccentric power is likely accounted for by the two-dimensional analysis of video, while the optical encoder was presumably able to detect movements in all three dimensions. The optical encoder detected movement in the horizontal plane during the eccentric phase that could not be detected on the two-dimensional analysis of the video analysis. This effect would only be present during the free-weight bench press since this lift was the only one that did not restrict movement through the horizontal plane in the Smith Machine. In this respect, the optical encoder was able to detect movement that even the criterion digital video analysis was unable to detect.

5.4.2 Use of the encoder to detect fatigue effects on power kinetics

Kinetic analyses over the four training sets indicated that peak power output in three of the four phases of the bench press, and overall mean power of the concentric movement, were substantially depressed as the four sets of six repetitions progressed. Decrements in peak power in the second (Figure 5.6) and third phase (Figure 5.7) were evident as early as the first set, but peak power during the first phase only started to decrease late in the fourth set (Figure 5.5), thus indicating the relative fatigue resistance of the first phase. Of particular interest was the finding that the repetitions where the peak power of the second phase approached zero (i.e. repetition failure) was the only repetitions in which the first phase peak power was also significantly lower than the first repetition. Power production during the second and third phases of each repetition is presumably dependent on voluntary activation of cross-bridge cycling of the active muscle groups, whereas power production during the first phase involves both voluntary activation and the stretch-shortening cycle, given that it is immediately preceded by the eccentric movement [96]. Consequently any impairment in voluntary force development during the first phase would have a lesser effect on peak power output as this would theoretically be compensated for by the relatively fatigue resistant stretch-shortening mechanisms [96]. The second and third phases of the concentric movement would be entirely dependent on voluntary activation of the required muscle groups, which explains their greater susceptibility to fatigue. Only when involuntary stretch-shortening cycle components begin to fatigue and are no longer adequately compensating for the dramatic impairment of voluntary force would peak power during the first phase decrease [95]. Since the first phase immediately precedes the sticking point and can dramatically add to the forced generation capability [76], the loss of power during the first phase leads to an inability to push through the sticking point. Therefore, repetition failure may be a key component to periodized strength training programs by training the capacity to generate enough power in the first phase to push through the sticking point [95, 254].

In conclusion, the Gymaware™ optical encoder provides a valid measure of power in a standard weight room setting. Changes in power output that occur over a typical bench press training session have also been described. Of particular interest was the relationship of power loss between the first versus the second and third phases of the bench press. The second and third phases were particularly sensitive to fatigue, evidenced by a substantial early decline in power. In contrast the first phase was relatively fatigue resistant, likely as a result of the contribution of the stretch-shortening cycle compensating for loss of voluntary force production. Once significant power is lost in the first phase, the loss of power during the sticking region becomes substantial enough to make task failure probable.

5.5 Practical Applications

The optical encoder is a portable device that provides valid measures of peak and mean power. Sport scientists could easily utilise optical encoders to analyse these training variables, in addition to the volume of work performed, during free-weight resistance training. These applications will help the sport scientist to, firstly, design studies with greater control over training variables to improve the quality of free-weight training research, and secondly, identify the mechanisms that underpin the acute responses and longitudinal changes to discrete training programs. Continuous monitoring of training could assist the strength and conditioning coach to more effectively modify strength and power programs. The capacity of Gymaware™

optical encoders to store accurate data over long periods of time is also a practical advantage to conditioning coaches. Coaches will be able to monitor the progress of athletes in performance variables such as power or movement velocity.

An additional application of this research for conditioning coaches is the understanding that movement kinetics change as fatigue progresses. Early power decrements of power in the third phase of the bench press indicate accumulating impairment of the voluntary component of the concentric movement of bench press. In contrast, power decrements occurring in the first phase presumably reflect additional impairment of the components of the stretch shortening cycle. Since the only significant declines in power of the first phase correspond with the level of power at the sticking point approaching zero (i.e. repetition failure), training to repetition failure is implicated in stimulating adaptation of the first phase to generate greater power by stimulating adaptation of the phase that is responsible for pushing through the sticking point.

The sticking point of the bench press has several biomechanical components in common the sticking point of other lifting techniques, such as the squat. The first biomechanical principle is that the muscle is in a stretched position, immediately after the elastic and neural energy is dissipated. According to the length-tension relationship, the myofilaments are in a mechanically unsound position to generate substantial muscle force when in this position. The sticking point also occurs when the moment arm of the lift is at its longest (e.g. the humerus is parallel to the floor during bench press, the thigh is parallel to the floor in the squat), resulting in the sticking point being at the point of greatest torque. This information also allows generalisations to be made about areas of low and high power in other lifting techniques.

CHAPTER 6: TRAINING LEADING TO REPETITION FAILURE ENHANCES BENCH PRESS STRENGTH GAINS IN ELITE JUNIOR ATHLETES

6.1 Introduction

Development of strength and power is paramount to success in most sports, especially those involving short-term, high-intensity efforts. There are many different approaches that conditioning coaches utilize to condition athletes, including plyometric training programs and contrast loading, though the most widely utilised across many sports is strength training [90, 91, 275]. Traditional strength training programs of three to four sets for six repetitions at an intensity of 80% of a subject's maximum lift [249] may compromise the development of speed in a given athlete [117], though it is important to recognise the role of strength in power [20, 196]. Proposed stimuli for maximal strength adaptation include tension on the muscle [304], the amount of time under tension [270], prolonged exposure to metabolites [102, 270], and fatigue [254]. If high tension on the muscle is important for strength development then fatigue should be avoided [102, 311], though such a theory would neglect the importance of training volume [249] and fatigue-induced metabolites [291] in the adaptation process.

As consecutive repetitions are performed, progressive fatigue elicits a gradual reduction in power output until no further repetitions can be performed [192]. The term exercise to "repetition failure" or "task failure" [152] is preferred over exercise to "maximal fatigue" since the muscle is not entirely fatigued at the point of failure, but rather cannot continue to move the given load beyond a critical joint angle [95].

This "sticking point" corresponds to maximal fatigue only at that joint angle and does not necessarily represent maximal fatigue of the entire muscle [95]. Therefore, training leading to repetition failure represents maximal voluntary fatigue for the muscle groups involved at their given sticking point with the mass being lifted since no more work at that intensity can be performed. While the entire muscle may be experiencing high levels of fatigue at the point of repetition failure, to describe it as maximally fatigued would be inaccurate.

Several studies have explored training to failure but not directly equated several important training variables within the experimental design such as volume (3 sets of 10 repetitions not to failure versus one set of 8-12 repetitions to failure) [185], duration of the training period (~four min versus >20 min) [102], or training intensities (60% versus 100% MVC) [165]. Other studies only used untrained subjects [10, 249] or single joint movements, and isokinetic or isometric machines [102, 164, 165, 254], which may not be directly relevant for most sporting applications that involve coordinating several joints for movements. Therefore, a protocol equating volume, time, and intensity of training in non-contact team sport athletes undertaking multiple-joint, free-weights training could elucidate valuable information about including training that leads to repetition failure into larger periodised programs.

The need for training leading to repetition failure to enhance strength is not universally accepted [102, 254] though this concept does have some experimental support. Several studies have demonstrated strength gains by using light weights (~15-60% MVC) with multiple repetitions to train to failure [28, 81, 165, 220]. Although it seems intuitive that equating the work volume and intensity would elicit equal strength gains, Rooney et al. showed that subjects who performed biceps curls until repetition failure attained significantly greater single repetition maximum (1RM) gains than subjects training without assistance but permitted short rest intervals between repetitions.

The purpose of this study was to investigate the importance of training leading to repetition failure in the development of upper body strength in elite junior athletes. By comparing two equal volume and intensity training programs, one to elicit repetition failure (high fatigue) and the other to allow completion of all repetitions, the importance of training leading to repetition failure could be investigated. The hypothesis was formed that the training leading to repetition failure group would elicit greater improvements in both 6RM bench press and bench throw power. With the exception of Rooney [254], no research has standardized the number of repetitions performed, the number of repetitions performed at each intensity), and the duration of the training time.

6.2 Methods

6.2.1 Experimental Approach to the Problem

Subjects were 26 highly trained junior basketball and soccer players. Each subject was assigned to one of two bench press training programs consisting of four sets of six repetitions or eight sets of three repetitions. Both groups trained an equal number of repetitions (24 total repetitions) at the same relative intensity of their six repetition maximum (85 – 105%) (approximately 85% 1RM, [54]) in an equal amount of time (13 min, 20 s), three times per week for six weeks. Pilot testing established that this design elicited sufficient fatigue for the four sets of six group to be unable to complete the final repetitions of the training program without the assistance of a spotter. In contrast, the eight sets of three group were able to complete all repetitions successfully. This design allowed us to evaluate the importance of training that leads to repetition failure without adding confounding variables of training volume, intensity, or time.

6.2.2 Subjects

The sample group consisted of 26 elite junior male team game players (basketball, n=12, age 18.6 ± 0.3 y, height 202.0 ± 11.6 cm, mass 97.0 ± 12.9 kg; soccer, n=14, age 17.4 ± 05 y, height 179.0 ± 7.0 cm, mass 75.0 ± 7.1 kg, mean ± SD). While this study was conducted on athletes in sports that do not typically have a major emphasis on upper body strength, all subjects had moderate to extensive weight training experience ranging from six months to three years, including the bench press. Subjects provided written informed consent for testing, training, data collection, and publication of results as part of their Scholarship Agreement with the Australian Institute of Sport (AIS), in accordance with requirements of the AIS Ethics Committee. Testing and training procedures were explained prior to the start of the study and subjects were informed that they could withdraw at any time without prejudice.

6.2.3 Experimental Procedures

In the initial week of the study subjects were tested on two separate days to determine the reliability of their 6RM bench press and maximal power generated during a Smith Machine bench throw with testing sessions were separated by at least two days with no resistance training during this time. Subjects were pair-matched for sport, 6RM, and the number of years completed on an AIS Scholarship, and then randomly assigned into either the repetition failure or the non-repetition failure groups. The matching process was intended to ensure groups were matched for training background and training potential. Subjects had not participated in extensive resistance training programs prior to commencement of their AIS scholarships. Thus, the number of years at the AIS was considered an accurate measure of resistance training age. Furthermore, the training period for this research occurred during the in-season phase so all players had been on a similar resistance and sport-specific training program for at least four months. No athletes were taking legal dietary supplements. Additionally, all were eligible for random testing by the World Anti-Doping Agency (WADA) and were therefore unlikely to be involved in any type of illegal doping. The training groups consisted of either training four sets of six repetitions to repetition failure (RF_{4x6}, n=15), or eight sets of three repetitions not to failure (NF_{8x3}, n=11). Both groups undertook a six-week training program of either training leading to repetition failure or non-repetition failure training. Upon completion of the training intervention, subjects were re-tested on 6RM bench press and Smith Machine bench throw power.

6.2.3.1 6RM Bench press

Subjects were evaluated on two tests, a free-weight 6RM bench press for strength and a 40kg Smith Machine bench throw for maximal mean power. Strength can be defined as the capacity to displace a known mass (kg) for a designated number of repetitions that met the technical criteria for the selected lift irrespective of the time taken to move the mass. Prior to testing, subjects performed a thorough warm-up involving 10 min of stationary cycling and three sets of bench press comprising 12 repetitions at

50%, 6 repetitions at 75%, and 3 repetitions at 90% of their 6RM. Previously documented training records were used as a guide for selecting the first test mass for determination of 6RM. Mass was progressively increased with each successful set of 6 repetitions, allowing a minimum of 180 s rest between attempts.

The technical criteria for bench press specified a pronated grip with hands spaced so that the subject's forearms were perpendicular to the bar when the bar was resting on chest. The subject was required to lower the bar without a pause until the chest was touched lightly approximately 3 cm superior to the xiphoid process. The bar was not permitted to stop at any point throughout the lift off the chest. The elbows were extended equally with the head, hips, and feet remaining in contact with the bench throughout the lift. Failing to meet any of these technical criteria constituted an unsuccessful attempt.

6.2.3.2 Bench Throw Power

On a separate day to the 6RM bench press testing, subjects were evaluated for maximal power output during a Smith Machine bench throw. The Smith Machine (Life Fitness, Victoria, Australia) consisted of a horizontal barbell mounted on two vertical rails to keep the bar level and allowing it to move only in the vertical plane. Bench throw power (40kg) was used as an independent test for maximal strength due to its high correlation with maximal strength [21] and performance in other power events [196]. The absolute load of 40kg was selected as it represented a relatively moderate load (~50% of most subjects 1RM) that could be directly compared with other research following the same protocol [20-22]. Prior to testing each subject completed a thorough warm-up involving 10 minutes of stationary cycling and three sets of bench press comprising 12 repetitions at 20kg, 6 repetitions at 30kg, and 3 repetitions at 40kg with 1-min rest between sets. Subjects then performed two sets of two 40kg bench throws every 35 s for a total of four throws.

Mean power was measured with a Micro Muscle Lab Power optical encoder (Ergotest Technology a.s., Langesund, Norway) attached to the bar. One end of the optical encoder cord was attached to the barbell and the other end coiled around a spool on the floor positioned perpendicular to the movement of the barbell. The optical encoder measures velocity and displacement of the barbell from the spinning movement of the spool while mass is entered via a keypad into the device. The sensitivity of load displacement was approximately 0.075mm with data sampled and velocity calculated at a frequency of 100 Hz. Power was calculated as the product of force and velocity. The entire displacement and time for the concentric phase were used to calculate the mean values for velocity, force and power. Subjects had two separate attempts performing two maximal throws. The mean power output was recorded for each throw and the highest mean power was used for analysis.

While the validation of the Gymaware optical encoder (Chapter 5) is the first in the series of bench press studies presented, the current chapter (Chapter 6) was the first to be conducted. The 'Micro Muscle Lab Power optical encoder' used in the present study presented with several methodological issues, such as its inability to store data, which made its use prohibitive for further research. These limitations were overcome with the Gymaware optical encoder validated in the previous chapter.

Both the 6RM and bench throw tests were repeated at least two days apart to establish test-retest reliability for these measures through calculation of the typical error of measurement (TEM) [147] and intraclass correlation R scores (ICC).

6.2.3.3 Determining the extent of fatigue

The Smith Machine bench throw was also utilised to evaluate the extent of muscle fatigue induced by each training protocol since training leading to repetition failure does not necessarily represent maximal fatigue [254]. Each subject performed the bench throw for power and then either the RF_{4x6} or the NF_{8x3} protocol. Assessment of bench throw power was then repeated three minutes after completion of the final repetition of the training protocol. At least three days apart, subjects performed the other training protocol. The percent decrement in bench throw power between the pre-training and post-training throws was used as an index of muscle fatigue from each protocol.

6.2.4 Training Program

Both groups completed a total 24 repetitions of the barbell bench press in a fixed time of 13 min and 20 s per training session at a frequency of three times per week, on alternate days, over a six-week training period. Prior to training subjects performed 5-10 min of stationary cycling as warm-up. Training intensities were assigned based on a percent of the athlete's 6RM testing [17]. The NF_{8x3} group performed 8 sets of 3 bench presses at intensities ranging from 80 to 105% of their 6RM (Table 6.1) with each set commencing every 113 s. The RF_{4x6} group performed 4 sets of 6 bench presses at the same intensity of their 6RM bench press (Table 6.1) with each set commencing every 260 s. The purpose of this design was for the failure group to work less frequently (i.e. four sets versus eight) but for longer periods (i.e. six repetitions versus three) while resting less frequently but for longer periods (i.e. 100 versus 230 s) than the non-failure group. By each group starting on zero seconds and continuing each set on the assigned time, and allowing 12 s to complete 3 repetitions or 20 s to complete 6 repetitions each group completed the training program in 13 min 20 s. Subjects performed all bench press training in a free-weight setting on an official Paralympic power bench using a standard 20 kg bar.

The assigned intensities by sets, sessions, and weeks of the program (Table 6.1) gradually increased the overall intensity over the course of the study while decreasing the intensity within each week. While the supramaximal loads used in the final weeks of the training program were employed to ensure that failing intensities continued to be experienced as each subject's strength increased over the study period, the lower intensities later in the week were used to avoid potential injuries of sustained failure training. Each training week (i.e. weeks 1-6, Table 6.1) involved three training sessions (i.e. Sessions 1-3, Table 6.1). Each set was undertaken at an assigned intensity of the subject's 6RM. During training weeks one to three subjects in the RF_{4x6} group trained at intensities increasing from 85%, 90%, 95%, and 100% in session one for the week (e.g. Monday, Table 6.1). Subjects in the NF_{8x3} group trained each of these intensities twice (i.e. sets 1-8 were at intensities of 85%, 85%, 90%, 90%, 95%, 95%, 100% and 100% respectively). The second training session of weeks one to three (e.g. Wednesday, Table 6.1) involved training all sets at 90% of the subject's 6RM. In the session three of the week (e.g. Friday, Table 6.1) during weeks one to three, all sets were trained at 80% of the subject's 6RM. In training week four the training intensity increased with the first training session of the week (i.e.

Monday, Table 6.1) being trained entirely at 95% of the subject's 6RM, while session two was trained at 90%, and session three were at 80%.

Table 6.1 - Number of sets trained in each session at each of the weekly training intensities expressed as a percent of 6RM

	Training Weeks 1 to 3				Training Week 4				Training Weeks 5 and 6			
RF4x6 Set	1	2	3	4	1	2	3	4	1	2	3	4
RF8x3 Set	1&2	3&4	5&6	7&8	1&2	3&4	5&6	7&8	1&2	3&4	5&6	7&8
Session 1	85	90	95	100	95	95	95	95	90	95	100	105
Session 2	90	90	90	90	90	90	90	90	95	95	95	95
Session 3	80	80	80	80	80	80	80	80	85	85	85	85

Spotters were instructed that if assistance was required, they should provide only the minimum amount of assistance required to continue the set. If assistance from the spotter was necessary, the number of assisted repetitions was recorded in the athlete's training diary, but all repetitions were completed, even if assistance was required on several repetitions. Weights used in each session were rounded to the nearest 2.5 kg. Apart from the formal requirements of this study, both groups performed similar whole body weight room training programs involving all major muscle groups of the body in a single one-hour training session.

6.2.5 Statistical Analysis

All raw data are expressed as mean ± SD while estimates of change and difference score are expressed as mean with 95% confidence limits. A Two-Way ANOVA with repeated measures was used to identify significant differences between groups in bench throw power for determining the extent of fatigue induced by each protocol. To establish the precision of the estimate of change, 95% confidence intervals were also calculated [158, 196]. The correlation coefficient between 6RM and 40kg bench throw was calculated using Pearson Product Moment. P-values were considered significant at $p<0.05$.

The repeat tests of bench throws and 6RM bench press collected in the first week of the study were analysed for TEM and ICC to quantify the variation in testing a subject over multiple test sessions [196]. TEM is an important measure to distinguish between a real result and the noise of a test; a change smaller than the TEM could simply be noise in the test. To determine the practical significance of observed changes, the smallest worthwhile change (SWC, equivalent to a small Cohen effect size) were assessed as 0.2 of the between-athlete standard deviation for each variable (SWC= 0.2xSD) [196]. The SWC is a useful tool to establish the clinical (practical) significance and especially in distinguishing between trivially small changes and those changes large enough to have a meaningful or worthwhile effect on performance [196]. Further analysis beyond statistical analysis was conducted to assess the likelihood of potential differences between programs on each test [196].

6.3 Results

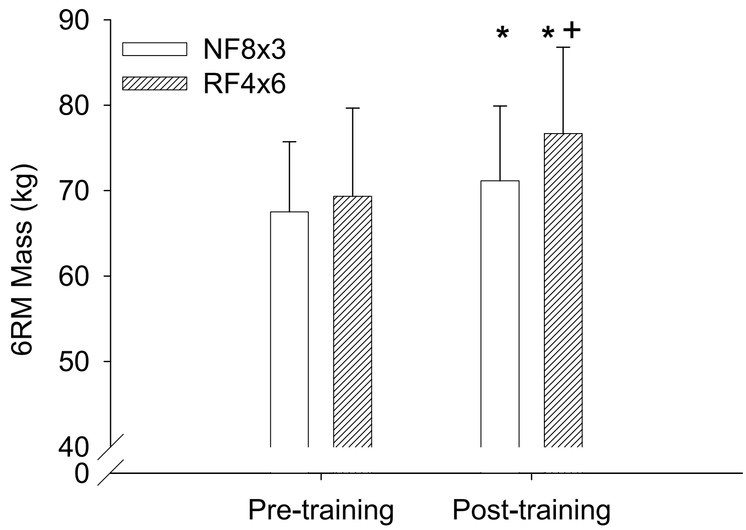
6.3.1 Bench Press

The TEM, ICC, and SWC of the 6RM bench press were 1.1 kg (1.7%), 0.86, and 1.8 kg (2.6%). Prior to training, there were no significant differences between the RF_{4x6} and NF_{8x3} groups in 6RM bench press (69.3 kg ± 10.3 versus 67.5 kg ± 8.2, respectively, $p=0.62$).

The RF_{4x6} group experienced a substantial increase in strength in 6RM (7.3 kg, 95%CL: 6.0 – 8.7 kg, p<0.001, Figure 6.1) after training that was two-fold greater (p=0.001, 95%CL: 1.2 – 6.2 kg) than the increase in 6RM in the NF_{8x3} (3.6 kg, 95%CL: 1.6-5.7 kg, p<0.005, Figure 6.1). Calculation of likelihoods reveals that there is a 92% probability that the true difference between the two groups is worthwhile in practical terms.

Figure 6.1 - Comparison of 6RM (kg) in the repetition rest and repetition failure groups

Bars represent the load of 6RM ± SD in each training group before and after training program. * Indicates p<0.05 greater than the pre-test. + Indicates p<0.05 difference between groups. Error bars represent the standard deviation of the group.



6.3.2 Bench Throw

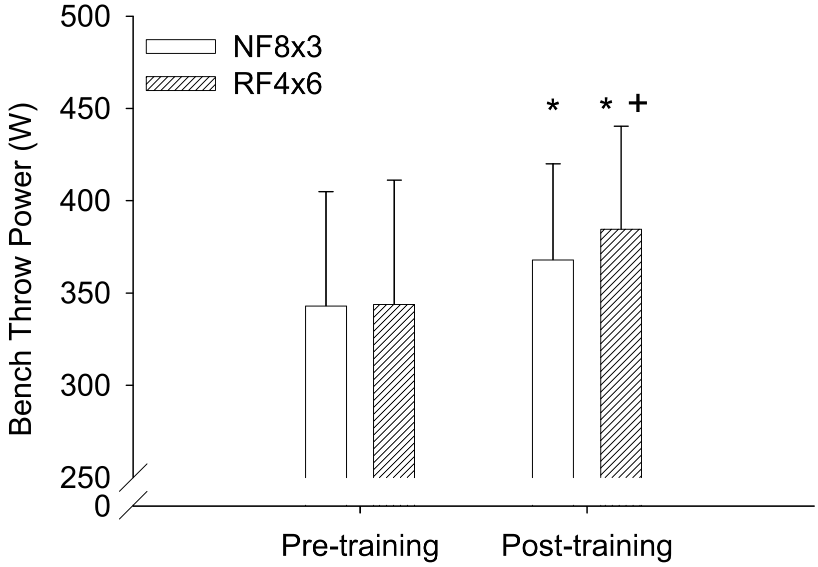
The TEM, ICC, and SWC of the bench throw power were 14 W (4.0%), 0.92, and 10 W (2.6%) respectively. There were no significant differences between the repetition failure and non-repetition failure groups in the 40kg bench throw (343 ± 67 W versus 342 ± 62 W, respectively, p=0.97).

The RF_{4x6} experienced a substantial increase in bench throw power (40.8 W, 27.5-54.1 W, $p<0.001$, Figure 6.2) that was on average 15.8 W more ($p<0.05$, 3.1 – 34.7 W) than the increase experienced by the NF_{8x3} group (25 W, 12.2 - 37.8 W, $p<0.001$, Figure 6.2). Calculation of likelihoods showed that differences between the two training protocols are not only statistically significant but also 96% likely to be practically worthwhile. While a likelihood of >75% should be considered likely to be beneficial, a likelihood of >95% indicates that the difference between the two training protocols could be described as being ‘very likely’ [196].

There was a strong correlation ($r=0.89$, $p<0.01$) between 6RM bench press and 40kg bench throw. With such a high dependence of bench throw power on strength, the decision was made that the Smith Machine bench throw would be a more sensitive test of strength than 1RM testing as it measures changes in Watts while 1RM measures only to the nearest 2.5 kg.

Figure 6.2 - Comparison of Smith Machine bench throw (W) in the repetition rest and repetition failure groups.

Bars represent the power of Smith Machine bench throw ± SD in each training group before and after training program. * Indicates p<0.05 greater than the pre-test. + Indicates p<0.05 difference between groups. Error bars represent the standard deviation of the group.



6.3.3 Fatigue and Failure

The RF_{4x6} group failed on more repetitions per training session (1.0 ± 1.3 repetitions) than the NF_{8x3} group (0.0 ± 0.2 repetitions) ($p<0.01$). This indicates that while the NF_{8x3} rarely failed on any repetitions the RF_{4x6} group usually failed on at least one repetition of the 24 attempted. This observation confirms the intent of the program design in equating the volume of work in an equal amount of time to induce repetition failure by the end of each training session in the RF_{4x6} group but not the NF_{8x3} group.

The decrement of power in the 40kg bench throws was 19.6% after the RF_{4x6} training protocol (62.9 W, 35.9 – 89.9, $p<0.01$) compared with 7.8% for the NF_{8x3} group (25.6 W, 7.7 – 43.6, $p<0.01$). While there were no significant differences between pre trials (p=0.47), the power in the RF_{4x6} group was 15.9% lower after training (48.4 W, 24.7 – 72.0, p=0.001). There was no order effect in which the protocols were tested.

6.4 Discussion

The major findings of this study were that the RF_{4x6} group experienced substantially larger gains in 6RM bench press and bench throw power than the NF_{8x3} group. The current findings clarify the role of training leading to repetition failure in strength training. The first advantage of the current protocol was that training intensity (i.e. percent of 6RM), training volume (i.e. total number of repetitions) and duration of training time (13 min, 20 s) were all equated. Secondly, a multi-joint dynamic contractions over multiple sets were utilised [102, 254], and thirdly, training effects in elite team sport athletes with weight training experience were investigated. By utilising eight sets of three repetitions for the NF_{8x3} protocol no external assistance by a spotter was required to complete the prescribed number of repetitions. In contrast, repetition failure occurred in at least one of the four sets of six repetitions performed by the RF_{4x6} group. This experimental design therefore allows the conclusion that the RF_{4x6} group's greater improvement in strength was the result of incorporating greater fatigue to the point of failure.

While determination of statistical significance is important for assessing probability, calculation of likelihoods is useful in determining the degree of practical (clinical) benefit of each training program [196]. The calculated likelihoods indicate that the practical difference between the two training programs can be described as "likely" for the 6RM test, and "very likely" for the bench press throw test [196]. By calculating the TEM and SWC for both tests, boundaries were provided for the interpretation of the results. The improvements obtained from the RF_{4x6} training protocol (strength 9.6% and power 10.6%) and the NF_{8x3} protocol (5.1 and 6.8%) can be considered real given their magnitude was greater than the magnitudes of both the TEM and SWC of the 6RM and (1.7% and 2.6%) and bench throw (4.0% and 2.6%).

To ensure that the training effect of improving 6RM was not simply a task-specific response to training sets of six repetitions, bench throw power output was measured as a novel test of strength. There was a high correlation between bench throw power and 6RM, supporting the notion that a task with a large resistance is dependent on strength to generate power [20, 196]. The bench throw has several advantages over a traditional 1RM test of strength. Primarily, the bench throw is a dynamic movement and largely independent of the strength of a single joint angle, giving it context validity to the ballistic movements of team sports. The bench throw can also be measured with much greater precision (i.e. in W) than a 1RM bench press, which is typically measured to the nearest 2.5kg. The greater improvements of the RF_{4x6} group demonstrated that the strength improvements in bench press existed throughout the bench press range of motion.

Fatigue represents a decreased ability to produce power [99]. This study has demonstrated that greater fatigue was induced by the RF_{4x6} protocol, since a greater decrement in bench throw power occurred after the RF_{4x6} protocol than after the NF_{8x3} protocol. Some authors conclude that fatigue should be avoided for strength development since fatigue reduces the force and power a muscle can generate [102, 304]. Previous data have demonstrated that decrements of power are greater in the 4x6 group than the 8x3 [192]. While no measurements of force were taken during training or testing, it can be inferred that velocity is lower (i.e. there was negative acceleration), and thus force is lower, in the 4x6 group. Therefore, it was concluded that declining force induced by fatigue does not inhibit strength development.

Other authors suggest that fatigue is a necessary component of resistance training [81, 254]. Motor units are recruited in response to a sub-maximal contraction in an assigned order so that not all motor units are active at once [109]. Repeated sub-maximal contractions elicit fatigue of the active motor units such that additional motor units must be progressively recruited in order to maintain force output [254, 265] . Therefore, at the point of repetition failure the maximal number of motor units was presumably activated, especially during assisted repetitions, a point that the repetition rest group did not reach. Since activating and overloading a high number of motor units is important to facilitate strength development [281, 304] the repetition failure group presumably experienced greater strength gains as a result of maximizing the recruitment of active motor units [200]. Training to failure might enable an athlete to maximise the number of active motor units and therefore the magnitude of the adaptations made by the nervous system.

While no measures of neuromuscular activity or hypertrophy were collected in this study, the large magnitude of changes in 6RM for the NF_{8x3} (5.1%) and RF_{4x6} (9.5%) groups and bench throw (means 6.8 and 10.6% respectively) in a six-week training period, coupled with the slow rate of hypertrophic [10] and architectural [3] improvements of muscle in trained individuals, leads us to speculate that the majority of the strength changes were related to neural adaptations. It is generally considered that neural adaptations predominate in strength training studies, where strength and/or

EMG increase disproportionately more than changes in muscle hypertrophy [29, 121]. Neural adaptations are most commonly presented in relation to the rapid strength development in novice weight lifters [29]. However, Hakkinen and associates [118, 122] have demonstrated increases in EMG even in experienced lifters when increases in training intensity occur. Increasing the intensity elicits neural adaptations in a greater number of motor units by maximising the number of active motor units active at one time.

One limitation of this design was that all subjects were involved in daily team practices and skills sessions in their respective sport appropriate to elite junior players. The researchers had no control over possible differences in training volume between subjects. Such a limitation is a necessary compromise to explore training interventions in elite athletes in a real weightroom situation compared with a controlled laboratory investigation. To minimize any effect of training variations, subjects were matched between groups for sport, training experience, and 6RM bench press. Additionally, while the subjects were highly trained athletes, they had only modest weight-training experience, particularly in upper-body training. Therefore the results still likely reflect reasonably early adaptations to strength training.

For many team sports a combination of strength and speed are necessary physical attributes. However with increasing physical demands on athletes and time demands on coaches, specific training methods that elicit concurrent improvements in both strength and power are clearly desirable. The current results suggest that coaches of junior team sport athletes may be able to maximise strength gains in their athletes by utilizing a conventional weight training program (e.g. four sets of six repetitions on barbell bench press) where the intensity is high enough to lead to repetition failure. Athletes often periodize heavy and light weights because frequent training to failure for extended periods of time is both physically and mentally challenging. Since no subject exhibited a decrement in 6RM or power test performance after either training intervention, this chapter can also conclude that team sport athletes do not necessarily have to train to failure to maintain and improve existing levels of strength.

6.5 Practical Applications

By training barbell bench press utilising a more conventional weight training program (4 x 6 reps) with assisted repetitions coaches can maximise strength gains in their athletes. The current research highlights the potential benefits of training leading to repetition failure by demonstrating larger strength and mean power gains over a 6-week training period. Further research to clarify the mechanism(s) by which training leading to repetition failure promotes strength gains is warranted. Additionally, in this study athletes are able to maintain strength levels without training to failure over a six-week training phase. Such an outcome is important to allow athletes to periodize their strength-training program for training blocks of failure and non-failure. Such an application would be appropriate in a setting involving young male team sport athletes with modest upper body strength training experience for a six-week block of a larger periodized program of free-weights training.

CHAPTER 7: INCREASED NUMBER OF FORCED REPETITIONS DOES NOT ENHANCE STRENGTH DEVELOPMENT WITH RESISTANCE TRAINING

7.1 Introduction

Determining optimal training methods for development of maximal strength is vital for elite athletes and has been the subject of many decades of research [182]. The previous chapter of this thesis demonstrated that greater gains in strength occurred after bench press training to the point in which junior athletes (basketball and soccer) could no longer lift the weight on their own (i.e. repetition failure) compared to training that avoided repetition failure. Rather than just training to the point of repetition failure, a common training practice for athletes and recreationally active individuals is to obtain the assistance of a spotter to continue several so-called forced repetitions after repetition failure has occurred. While being widely advocated [89], only a few anecdotal reports of the actual performance of forced repetitions exists [50, 309]. Only one article exists in a peer reviewed source investigating the effect of forced repetitions on hormone levels, demonstrating higher levels of cortisol and growth hormone during training when subjects trained using forced repetitions [11]. Importantly, no studies have investigated whether performing multiple sets of forced repetitions enhances muscular strength adaptation [288]. Therefore, the primary goal of this research was to determine whether training that included a high number of forced repetitions generated greater strength gains than training with only a low number of forced repetitions.

Modification of training variables such as volume, intensity, and power all play an important role in strength development [182]. While the adage of "more is better" is tempting to coaches and athletes, greater volume and intensity have been shown to improve training-induced strength adaptations but not in a dose-dependent manner [111]. Diminishing returns occurred when volumes exceeded two days per week, with 4-8 training sets per muscle group [236, 249]. The indication that strength adaptations are dose-dependant only to a defined volume questions the usefulness of additional volume, particularly if the volume is gained through forced repetitions. Thus, the second aim of the current study was to determine if volume of work performed would affect the magnitude of strength development when repetition failure was reached.

A key consideration in strength research is control of important training variables such as concentric time, power output, and total work performed [71]. Unfortunately, resistance training research has been greatly limited by the difficulties in controlling these training variables [71, 288]. With the recent development of optical encoder technology [72], monitoring these variables throughout the training program is now possible. However, no studies have controlled for potential differences between training groups in these variables such as concentric time, power output, and total work performed. Therefore, a novel aspect of the study was application of an optical encoder to verify equality in concentric time, power output, and work completed between groups.

Therefore two hypotheses were tested in athletes with resistance training experience undertaking a bench press training program. First, that training with a high number of forced repetitions, but the same training volume, would elicit similar strength development than training involving a low number of forced repetitions. The second hypothesis of this chapter is that training with an increase in both number of forced repetitions and volume would fail to elicit substantially greater strength development.

7.2 Methods

7.2.1 Approach to the Problem

Each subject undertook a series of muscle strength and power tests, before and after a six-week training strength training intervention. These tests comprised the bench press 6 repetition maximum (6RM) and 3 repetition maximum (3RM), as well as the maximal power generated during a 40kg Smith Machine bench press throw (BT). Both 6RM and 3RM testing were conducted to evaluate if training specific responses to the number of repetitions the subjects performed in training were present. Each test was separated by at least two days. After pre-training testing, subjects were matched and then assigned to one of three training groups comprising either 4x6, 12x3 or 8x3 (sets x repetitions). Each group was therefore different in training volume and number of forced repetitions. After six weeks of training all subjects were re-tested and evaluated for change in 6RM, 3RM, and 40kg Smith Machine bench press throw.

7.2.2 Subjects

Subjects were male elite basketball players (n=12) and elite volleyball players (n=10). Subject physical characteristics are summarised in Table 7.1. All players were in the 'maximal strength' training block of their respective periodised programs at the time the study began, resistance training three days per week on non-consecutive days. Subjects provided written consent for testing as part of their scholarship arrangements with the Australian Institute of Sport (AIS), in accordance with requirements of the

AIS Ethics Committee. Testing and training procedures were explained prior to the start of the study and subjects were informed that they could withdraw at any time without prejudice. No athletes were taking legal dietary supplements. Additionally, all were eligible for random testing by the World Anti-Doping Agency (WADA) and were therefore unlikely to be involved in any type of illegal doping.

7.2.3 Matching of subjects prior to training

Prior to assignment into experimental groups, subjects were matched for sport, 6RM bench press, and training age for bench press. The matching process ensured that groups were similar for training background and training potential, with a balanced division of junior and senior athletes. The training age, defined as the amount of time each subject had been on a regimented resistance training program for bench press, was determined based on each athlete's individual weight room record.

7.2.4 Rationale for Experimental Groups

The program was designed such that two of the groups trained at equal volume (4x6 and 8x3), while an additional group trained at a higher volume (12x3). In addition, two of the groups trained with a similar higher number of forced repetitions (4x6 and 12x3), while one group trained with fewer forced repetitions (8x3). A key aspect of this design was that two of the groups trained at equal mean power outputs (8x3 and 12x3) while one trained at a lower mean power out put (4x6). To verify that expected differences in work, power, and concentric time between groups were present, movement kinematics for each repetition of every subject were measured for the duration of the training period with a GymAware™ optical encoder (Kinetitech Performance Technology Pty Ltd, Canberra, Australia).

Table 7.1 - Summary of Age and Anthropometric Measures of Participants

	Age (y)	Height (cm)	Body Mass (kg)	Sum of 7 Skinfolds (mm)	Estimated Fat Mass (kg)	Estimated Muscle Mass (kg)	Estimated Muscularity (%)
Basketball, n=12 (mean ± SD)	18.6 ± 0.4	200.7 ± 11.0	96.5 ± 11.7	52.0 ± 13.4	8.5 ± 2.4	45.9 ± 5.9	46.8 ± 1.3
Volleyball, n=10 (mean ± SD)	24.4 ± 3.0	197.3 ± 6.5	92.7 ± 8.6	55.3 ± 5.5	8.5 ± 0.8	44.3 ± 4.7	46.8 ± 1.1

7.2.5 Anthropometric Measures

Stretched height was measured during inspiration using a stadiometer (Holtain Ltd. Crymych, Dyfed). The typical error of measurement (TEM) for measuring height, including biological variation, was typically not more than 1% [229]. Beam balance or digital scales were used to measure body mass to the nearest 0.1 kg with a TEM between days, including biological variation, of 1% [229]. Skinfolds comprised the sum of seven skinfold thicknesses from triceps, subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf measured with Harpenden calipers (British Indicators Ltd., West Sussex, United Kingdom), with a TEM of the current anthropometrist of <2% [229].

Four-way fractionation of body composition was used to partition total body mass into four different constituent compartments: fat mass, residual mass, muscle mass and bone mass according to methods outlined previously [319]. The anthropometric profile consisted of the following measurements: height, mass, seven skinfolds, eleven girths, eight lengths, and eight breadths. The four compartment masses were estimated individually by measuring a representative subset of lengths, breadths and girths scaled for a known height and mass. The percent muscle mass was derived as the percentage of estimated muscle mass to the estimated total body mass. The TEM values of the current anthropometrist for estimating the fractionation components were: fat mass (0.1 kg, 1.4%), residual mass (0.2 kg, 0.9%), bone mass (0.2 kg, 1.3%), muscle mass (0.2 kg, 0.7%), and % muscle mass (0.2%, 0.5 %). The same anthropometrist conducted all measurements both pre- and post-training.

7.2.6 6RM and 3RM Bench Press

To test 6RM bench press and a 3RM bench press, subjects completed a warm up and were evaluated according to criteria described in the previous chapter. Briefly, athletes lowered the bar without a pause until the chest was touched lightly approximately 3 cm superior to the xiphoid process. The elbows were extended equally with the head, hips, and feet remaining in contact with the bench throughout the lift. Previously documented training records were used as a guide for selecting the first test mass for determination of 6RM. Mass was progressively increased with each successful set of 6 repetitions by an amount self selected by the subject, typically by 2.5 or 5 kg, allowing a minimum of 180 s rest between attempts. Both the 6RM, 3RM, and bench press throw tests were repeated on separate days to establish test-retest reliability for these measures through calculation of the TEM.

7.2.7 Bench press throw Power

Subjects were evaluated for maximal power output during a 40kg Smith Machine bench press throw measured with an optical encoder. The absolute load of 40kg for the bench press throw was utilised to compare results with Baker's studies of rugby league players [20]. Subjects performed two sets of two bench press throws every 35 s in a Smith Machine against 40 kg for a total of four throws. The mean power output (W) was recorded for each throw. Prior to testing each subject completed a thorough warm-up involving 10 min of stationary cycling and three sets of bench press comprising 12 repetitions at 20kg, 6 repetitions at 30kg, and 3 repetitions at 40kg with 1-min rest between sets. This procedure was repeated on separate days to establish test-retest reliability for power output of the bench press throw measures through calculation of the TEM.

7.2.8 Optical Encoder

A Gymaware™ optical encoder was used for continuous monitoring of all repetitions during training of concentric duration and mean concentric power. The concentric duration and mean concentric power were collected on each of 11,000 bench press repetitions performed in the study, thus allowing us to confirm that the equality between groups in power output and concentric time.

The displacement and velocity of each bench press repetition was measured with an optical encoder. This device consisted of a spring powered retractable cord that passed around a pulley mechanically coupled to an optical encoder, with the end of the cord attaching to the barbell. The device was positioned on the floor perpendicular to the movement of the barbell and measured velocity and displacement of the barbell. The device gives one pulse approximately every 3 mm of load displacement. Each displacement value is time-stamped with a 1 ms resolution. Position - time data points are generated at a maximum rate of 25 Hz. The entire displacement (mm) and time (ms) for the movement were used to calculate mean values for power.

7.2.9 Training Program

Each group trained three times per week on alternate days over the six-week training block. The six-week training intervention was chosen to correspond to the maximal strength training phase in the team sport athlete's strength and conditioning program within their annual cycle.

Experimental groups trained either 4 sets of 6 repetitions with each set commencing every 2 min, 45 s (4x6, n=7), 8 sets of 3 repetitions commencing every 1 min, 13 s (8x3, n=7), or 12 sets of 3 repetitions commencing every 1 min, 13 s (12x3, n=8). All groups trained at the following intensities of their 6RM in each session: 90% for the first 25% of their sets, 95% for the next 25% of their sets, and 100% of their 6RM for the final 50% to ensure repetition failure towards the end of the training session (Table 7.2). Training sets of 3 or 6 repetitions were used to elicit different amounts of fatigue but no group consistently trained at 100% of their 3RM; only at 90-100% of their 6RM. As each subject's strength gradually increased over the duration of the study, the weights were systematically adjusted to ensure repetition failure was reached in each session for the duration of the study. Spotters were instructed to provide only a minimum amount of assistance necessary to allow the subject to continue the set. Subjects were instructed to complete all repetitions in all sets, even if assistance on several repetitions was required. The number of assisted repetitions was recorded in the athlete's training diary. All training was directly supervised by the investigators to ensure quality and compliance of training [204]. Subjects performed all bench press training in a free-weight setting on an official Paralympic power bench using a standard 20 kg barbell.

Table 7.2 - Summary of training group programs illustrating differences in training intensity as a percent of 6RM, starting time, and the number of repetitions performed in each set

Training Group	Training Set	1	2	3	4	5	6	7	8	9	10	11	12	Total
4x6 (n=7)	Intensity (%)	90	95	100	100									End
	Cumulative Start Time (min:s)	0	2:45	5:30	8:15									8:45
	Number of Repetitions	6	6	6	6									24
8x3 (n=7)	Intensity (%)	90	90	95	95	100	100	100	100					End
	Cumulative Start Time (min:s)	0:00	1:13	2:26	3:39	4:52	6:05	7:18	8:31					8:45
	Number of Repetitions	3	3	3	3	3	3	3	3					24
12x3 (n=8)	Intensity (%)	90	90	90	95	95	95	100	100	100	100	100	100	End
	Cumulative Start Time (min:s)	0:00	1:13	2:26	3:39	4:52	6:05	7:18	8:31	9:44	10:57	12:10	13:23	13:37
	Number of Repetitions	3	3	3	3	3	3	3	3	3	3	3	3	36

Weights used in each session were rounded to the nearest 2.5 kg. Other weight room training by all groups involved 5-10 min stationary bicycling as warm-up, a traditional 60 min whole body routine involving all major muscle groups of the body, and 10 min stretching on cool-down. No other lifts in their training program specifically targeted similar muscle groups in a task-specific way to bench-press (e.g. incline dumbbell presses, etc.), but the synergistic involvement and therefore potentially additional training effects of the triceps, pectoral groups, and deltoids during other lifts cannot be entirely ruled out. Regardless, with the exception of the bench press all athletes performed training programs based on the same design, so any additional effects would affect all subjects. Other sport-specific training by all subjects involved daily team practices and skills sessions in their respective sport appropriate to elite (i.e. international) level players.

7.2.10 Statistical Analysis

All raw data are expressed as mean ± SD. Estimates of mean change and difference scores are expressed as mean with 95% confidence limits to establish the precision of the estimate (95% CL). After collecting dependent variables and assignment to groups prior to training, groups were compared for statistically significant differences by one-way ANOVA to ensure groups were evenly matched. Change scores after the training intervention of the 3RM and 6RM bench press (kg) and the maximum 40 kg bench press throw power (W) were analysed using a two-way ANOVA with repeated measures and Tukey HSD post hoc analysis. Significance was accepted at $p<0.05$.

Pre- and post- training data were pooled for each dependent variable and Pearson-Product Moment correlation coefficients were used to assess the degree of association between 6RM, 3RM and Smith Machine bench press throw measures. The TEM was calculated from the standard deviation of the change score (difference) between trials divided by the root of two. The TEM is a measure of variation within each subject and represents the magnitude of variability within an athlete in repeated test results [147]. The smallest worthwhile change of estimated changes was also calculated for 6RM, 3RM, and bench press throw power (SWC= 0.2 x between-subject SD) [68]. Comparison of the magnitudes of the TEM and SWC can be used to establish the practical importance of the results, by distinguishing between trivially small changes and those changes large enough to have a meaningful or worthwhile effect on performance.

7.3 Results

7.3.1 Pre-Training Testing

7.3.1.1 Relationship between strength and power

The three groups were equivalently matched in bench press strength and bench press throw power prior to the training intervention program, with no statistically significant differences found between groups (Table 7.3). Pooled measures of bench press strength (6RM and 3RM) and bench press peak and mean power were highly correlated ($r=0.77$ for both 6RM and 3RM to mean power; $r=0.83$ and 0.85 for 6RM and 3RM to peak power, respectively, all $p<0.01$).

Table 7.3 - Summary of pre-training strength and power testing comparing groups

Test	12x3 (n=8)	4x6 (n=7)	8x3 (n=7)	p-value
6RM (mean kg ±SD)	75.0 ± 10.5	77.1 ± 6.0	75.7 ± 10.9	0.91
3RM (mean kg ±SD)	80.9 ± 11.1	82.9 ± 6.8	80.7 ± 11.9	0.91
Bench Press Throw Peak Power (mean W ±SD)	597.5 ± 67.9	582.9 ± 82.6	584.5 ± 152.6	0.96
Bench Press Throw Mean Power (mean W ±SD)	318.6 ± 24.9	334.6 ± 63.5	317.6 ± 54.3	0.77

7.3.1.2 Assessing Magnitudes of Change

The smallest worthwhile changes in this sample of basketball and volleyball players were: bench press throw peak power 23.2 W (~4.0%); bench press throw mean power 10.3 W (~3.1%); 6RM 2.0 kg (2.5%), and 3RM 2.0 kg (~2.5%). The TEM of the 6RM, 3RM, and bench press throw peak and mean powers were 1.1 kg (1.7%), 1.8 kg (2.0%), 46.2 W (15%), and 16.3 W (11.2%) respectively for all measures (Figure 7.1, n=22). These data indicate a greater likelihood of strength testing showing a substantial improvement, given the relatively larger TEM for power.

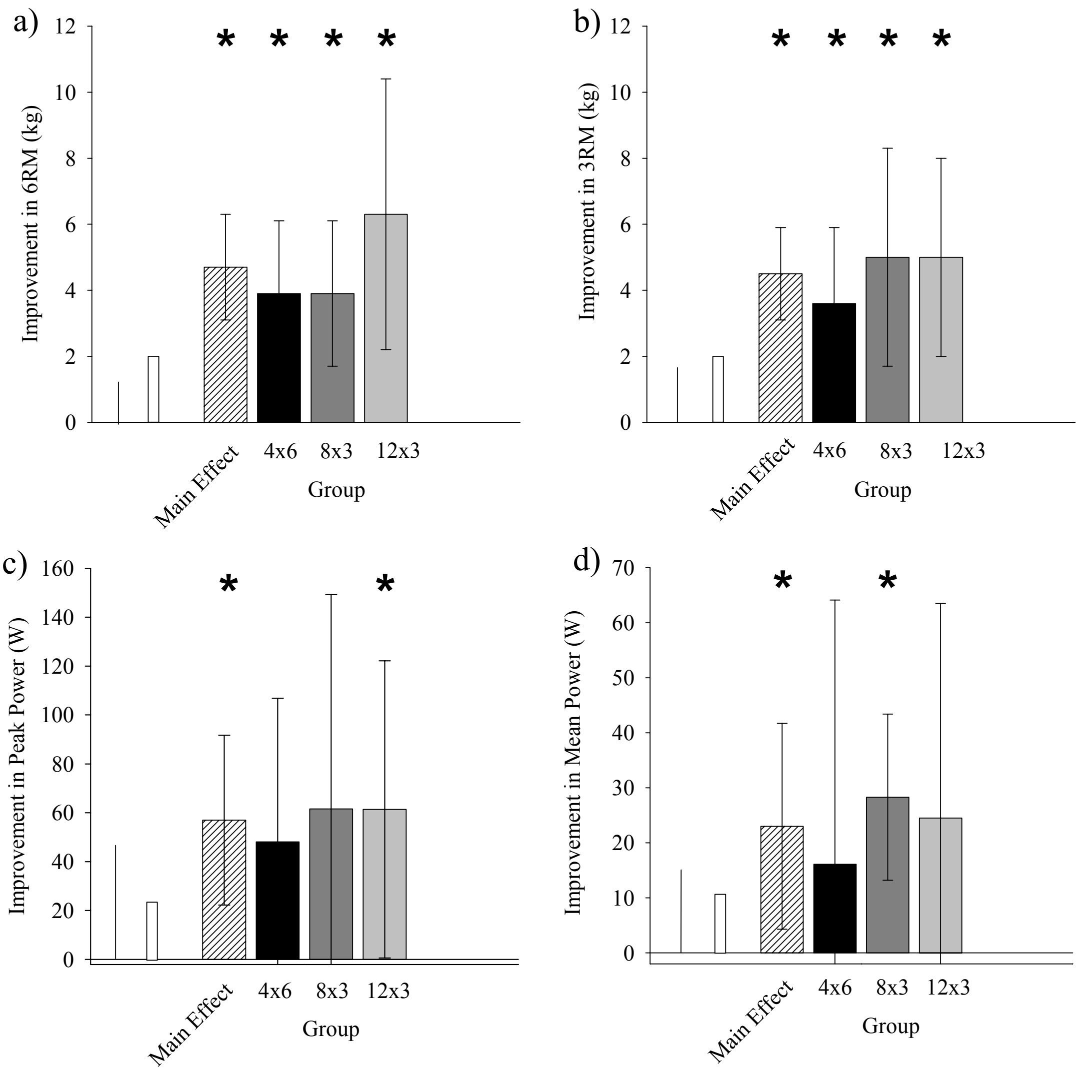
7.3.2 Training Analyses

7.3.2.1 Training Compliance

There were no significant differences in the number of training sessions attended by each subject over the course of the study (4x6= 81%, 8x3= 80%, 12x3=78%, p=0.30). Reasons subjects missed training sessions included injury, illness and/or absence from the gymnasium due to other specified training, travel, education, or competition commitments.

Figure 7.1 – Changes in strength and power of different groups

Change scores in different tests comparing the 4x6 (n=7), 8x3 (n=7), and 12x3 (n=8) groups after six weeks of bench press training. Tests were a) 6RM, b) 3RM, c) bench press throw peak power, and d) bench press throw mean power. Individual lines (|) represent the smallest worthwhile change (SWC) while open bars (▯) represent the typical error of measurement (TEM) of the test. Main effect refers to the change score for all groups combined. Error bars represent 95% confidence limits while asterisks indicate statistically significant improvement ($p<0.05$) compared with pre-training.



7.3.2.2 Number of Forced Repetitions

All subjects completed all prescribed repetitions of all training sessions. The number of failed repetitions indicates the number of repetitions per training session that the subject needed assistance from the spotter to complete the prescribed total repetitions. Both the 4x6 and 12x3 groups achieved the desired outcome of a higher number of repetitions to failure than the 8x3 group. The 4x6 group failed on a greater number of repetitions than the 12x3 group (1.0, 95% CL 0.07 to 1.9, p=0.03) and the 8x3 group (2.9, 2.0 to 3.8, p<0.01) while the 12x3 group failed more than the 8x3 group (1.9, 1.0 to 2.8, p<0.01) (Table 7.4).

7.3.3 Kinematic Analysis of Bench Press

7.3.3.1 Concentric time

The high volume 12x3 group had significantly greater concentric time than the other two equivalent groups. The mean concentric time per training session was similar between the 4x6 and 8x3 groups (0.2 s, -5.0 to 4.6, p=0.99). In contrast, the concentric time was higher in the 12x3 than in the 4x6 group (18.0 s, 13.2 to 22.8 s. p<0.01) and the 8x3 group (17.8 s, 13.2 to 22.4 s, p<0.01) (Table 7.4). These data verify that the groups assigned the same training volume exercised for a similar concentric time, but the 12x3 high volume group also had a higher concentric time.

7.3.3.2 Total Work

The high volume 12x3 group performed greater work than the other two groups which were equivalent. The total work performed per training session did not differ between the 4x6 and 8x3 groups (784 J, -413 to 1982). However, the 12x3 group performed more total work than the 4x6 group (10,720 J, 9527 to 11,913 J) and the 8x3 group (9935 J, 8784 to 11,087) (p<0.01, Table 7.4).

Table 7.4 - Comparison between groups on kinetic analysis

Data represents the group mean (±SD) per training session in each kinetic property assessed.

Training Group	12x3 (n=8)	4x6 (n=7)	8x3 (n=7)
Concentric Time (s)	57.2 ± 13.2*	39.2 ± 6.1	39.4 ± 9.8
Total Work (concentric + eccentric J)	26,591 ± 3020*	15,871 ± 1985	16,655 ± 2502
Concentric Mean Power (W)	281 ± 57	251 W ± 41[+]	280 ± 54
Failure Rate per training session	3.1 ± 3.5[u]	4.1 ± 2.6[au]	1.2 ± 1.8

* statistically higher than 4x6 and 8x3 ($p<0.001$)

[+] statistically lower than the 8x3 and 12x3 groups ($p<0.001$)

[a] statistically higher than the 8x3 and 12x3 groups ($p\leq0.03$)

[u] statistically higher than the 8x3 groups ($p<0.01$)

7.3.3.3 Concentric Mean Power

There were no significant differences in the concentric mean power output per training session between the 8x3 and the 12x3 groups (0.6 W, -23.8 to 22.7, p=0.99). In contrast, the concentric mean power of the 4x6 group was significantly lower than both the 8x3 groups (-29.1 W, -5.0 to -53.3, p=0.01) and the 12x3 groups (-29.7 W, -5.6 to -53.8, p=0.01) (Table 7.4).

7.3.4 Effects of Strength Training

7.3.4.1 Strength and Power Test

The main effect of training illustrated improvement in all tests of strength and power. The 6RM improved from 75.9 to 80.6 kg (p<0.01) while 3RM improved from 81.5 to 86.0 kg (p<0.01). Smith Machine bench press throw peak improved from 589 to 646 W (p<0.01) and mean power improved from 323 to 346 W (p=0.02). All changes exceeded the TEM and SWC and consequently could be considered as real and worthwhile. There were no significant differences between groups on any of the improvements (Figure 7.1 a-d).

7.3.4.2 Anthropometric Changes

Several of the changes in anthropometric measures were statistically significant but unlikely to have been practically worthwhile. Over the study, chest circumference increased by a mean of 0.5 cm (0.03 to 0.89, p=0.04) for all subjects, though the SWC was 0.9 cm. Estimated muscle mass increased by 0.6 kg (0.36 to 0.90, p<0.01) though the SWC was 1.1 kg. A 0.2 kg decline of fat mass (0.0 to 0.4 kg, p=0.05) though the SWC was 0.4 kg. However there was a 0.4% increase in percent muscularity (0.1 to

0.6%, p<0.01, SWC=0.24%). There were no significant differences between groups in muscularity.

7.4 Discussion

These results have important practical implications for the design of optimal training programs in challenging the efficacy of the widespread training practice of increasing the number of forced repetitions and set volume to enhance strength gains. A major finding was the absence of any differences in the magnitude of the strength or power gains when the number of forced repetitions was increased and training volume was held constant. This observation indicates that increasing the number of forced repetitions does not further increase strength or power gains with training. A second finding of the study was that increasing both the number of forced repetitions and training volume did not enhance strength or power gains. Hence the lack of effect with number of forced repetitions cannot be explained by a failure to increase training volume. These results indicate that there is no additional benefit to strength or power development when training repeated sets of forced repetitions, compared to ceasing training sets once the point of repetition failure has been reached.

The perceived benefit of forced repetitions in the resistance training community is that the extra volume of training will enhance training adaptations, even if the added volume is performed with assistance. Training to the point of repetition failure has received some empirical support for developing strength and power [254]. The results of the current study clearly do not support any additional benefit of repeated forced repetitions, or the need for additional volume with respect to enhancing the development of strength, power, or hypertrophy. While higher volumes of training are important to developing muscular strength and hypertrophy in athletes, the effect does not appear to be entirely dose dependent [249, 270].

An important feature of this study was the implementation of the optical encoder to quantify bench press kinetics of the subjects for each repetition, and to quantify the total volume of work performed, total concentric time, and mean power exerted by each group per training session. These measurements verified that training volume, time, and number of repetitions was indeed greater in the 12x3 group and were matched in the 4x6 and 8x3 groups (Table 7.4). These findings permit the exclusion of the possibility that the observed results where influenced by differences in total volume of work, power output, concentric time, or the rates of failure. It is rare in resistance training studies investigating the relevance of fatigue and failure to control for variables such as time to completion [102] and training intensity [11, 165]. Even when such variables are controlled, there is no assurance that key training variables such as concentric time, total work, or power output are also equivalent [71]. Thus this thesis chapter substantially advances the methodological approaches taken in the literature. Finally, given the importance of manipulating volume, intensity, and power in eliciting different resistance training responses [182], continuous kinetic monitoring could become a regular part of free-weight resistance training studies [71].

Improvements in strength and power in the current study were greater than the magnitude of anthropometric changes, a phenomenon that has primarily been linked to neural adaptations [29]. Other researchers have previously reviewed the neural [29], metabolic [262] and ionic [112] mechanisms proposed to contribute to muscle fatigue and failure. The dominant cause of failure during very high intensity training has been linked to central and neural mechanisms such as antagonist (co-) activation and agonist (recurrent) inhibition [29, 30]. While neural adaptations traditionally are perceived to occur only in the initial weeks to months of training in novice strength trained athletes before stabilizing after this period [29], EMG studies have demonstrated that even experienced lifters make neural adaptations when presented with a new, higher intensity, training loads [122]. Therefore, the improvements demonstrated in the current study are more likely derived from neural adaptations. Improved membrane excitability, consequent to upregulation of muscle Na^+,K^+-ATPase may also underpin the improvement seen with training [272].

7.5 Practical Applications

The present study has demonstrated that multiple sets of forced repetitions convey no further benefit to strength development over ceasing training when failure is reached, even when higher volumes of both successful and failed repetitions are completed. While repetition failure is an important inclusion to a strength development program [254] failure training should not be maintained year-round, as manipulating training intensity is an important part of strength development [24, 122]. Strength and conditioning coaches are well aware that training at high intensities for prolonged periods of time can lead to athlete burn-out, injury, and overtraining syndrome [35]. This study suggests that the common practise of utilising forced repetitions is not beneficial and should therefore be minimised when strength development is the goal. Limiting the number of forced repetitions would also reduce the stress on athletes and contribute to a more manageable training load. In conclusion, in this study where repetition failure was reached in each training session, further increasing the number of forced repetitions or set volume did not affect the magnitude of the strength gains.

The application of this research centers on athletes that have moderate levels of resistance training experience and a short training cycle to develop maximal strength. For example, an American collegiate sport coach may recruit a young player (e.g. 17 y) at the end of a school year (e.g. June). The player performs a home training program for general strength over the summer months prior to the start of the collegiate program (e.g. September) in order to begin their sport training program with a basic level of strength. At the start of the scholastic year, the team sport coach therefore has only a limited time (e.g. 8 weeks) to begin a supervised resistance training program on an athlete with a moderate training background prior to the commencement of the competitive season (e.g. November). The current research findings illustrate that the team coach, or the team conditioning staff should not use valuable preparation time in high volume, high forced repetition training in the hope of developing greater strength, power, or muscular development. This study has investigated strength development in athletes who are not specifically trained for strength. While strength, power, and hypertrophy are important aspects of sports such as basketball, American football, and rugby, these athletes are not ranked on strength, power, and size alone as in powerlifting, Olympic weightlifting, or bodybuilding. Coaches and sport scientists should be cautious when applying the results of this research to pure strength, power, and hypertrophy athletes.

CHAPTER 8: THESIS DISCUSSION AND CONCLUSION

The general aim of this thesis was to systematically evaluate trends in the development of body size, strength, and power in highly trained (junior) basketball players, and to determine the relative effectiveness of resistance training programs employing repetition failure in developing these qualities. The results show that resistance training involving training to repetition failure elicited greater improvements in muscular strength compared with non-repetition failure training. Further investigation revealed that additional training volume and additional numbers of forced repetitions yielded no further enhancement of muscular strength and power. On the basis of these findings, the maximal strength phase of a resistance training program for junior basketball players should include mesocycles of training to the point of repetition failure, without the use of forced repetitions, during strength development phases.

8.1 Modeling fitness trends

8.1.1 Differences between newly recruited players

The initial studies of this thesis were prompted by concerns of the apparently diminishing fitness and body size of players recently recruited into Australian junior basketball programs when compared to their international counterparts. Initial investigations involved analysis of six years of retrospective fitness and anthropometric testing records from Basketball Australia (BA) and the Australian Institute of Sport (AIS). The findings confirmed hypothesis #1 that discrete aspects of fitness of first-year players entering State and National junior levels have been declining in recent years. The secular effect on body size was less clear with height remaining generally stable but body mass declining slightly. Hypothesis #2 was also confirmed in the finding that a substantially greater fitness and body size, and lower variability in test scores, of senior ranked players relative to their lower ranked counter-parts. This finding demonstrates the value of body size (i.e. standing stature and body mass) and physical fitness (i.e. lower body power and aerobic endurance) in the National level of Australian basketball. This experimental confirmation is consistent with Australian basketball coaches' anecdotal reports that the body size and fitness test scores have been declining in recent years.

8.1.2 Changes within players over time

Further retrospective analysis failed to support hypothesis #3, that players would substantially improve body composition and fitness over multiple years in their respective programs. The results revealed that changes (generally improvements) in tests of lower body power and body mass for given players were typically only trivial to small in magnitude. The failure to demonstrate substantial improvement in fitness was evident even though many players spent extended periods of time in State and National training programs. Hypothesis #4 of little improvement in body composition and fitness between individual phases of a competition year was confirmed. While these results appear initially surprising given the high intensity nature of elite basketball training, other studies investigating fitness changes over a basketball season, or over multiple seasons, have also reported relatively modest changes [62, 113, 141, 151, 293]. Hypothesis #5 was also confirmed in that substantial individual variation in fitness existed within players, indicating that while the fitness levels of groups of players tend not to change as a whole, individual players can make considerable personal improvements. Substantial individual variation likely obscures small to moderate group changes in fitness, however it is this same variation that coaches, players, and conditioning staff must account for in the planning, execution, and review of fitness training programs. The findings of only modest changes in size and fitness within players prompted questioning of the efficacy of current resistance training programs in highly trained junior basketball players.

8.2 Resistance Training

8.2.1 Gymaware validity to measure bench press kinetics

Recent research has revealed the potential for heavy resistance training traditionally used to develop strength to improve sport-specific power output in actively training athletes [44, 75, 142, 196, 208]. The primary difficulty in conducting research on free-weight resistance training programs is ensuring control of important training variables between training groups [75]. A recent technological advance allowing measurement of these factors is the development of an optical encoder device that logs time and position data of free-weight resistance training (barbell) movements. However, very little data exists confirming the validity of such devices to accurately and reliably monitor free-weight movement kinetics [72]. Therefore, before optical encoders can be utilised to study free-weight resistance training programs, their reliability and validity to measure power must be established. Hypothesis #6 of this thesis was that the optical encoder would be a valid tool for measuring power during free-weight resistance training activities. The results of Chapter 5 show that the optical encoder had an SEE for power ranging from 3.6 to 14.4 W (CV, 1.0-3.0%; correlation, 0.97-1.00). The CV established here is similar to that which occurs within an athlete between training days (1-5%) [192] and when comparing similar devices to a force plate (2-8%) [72]. Collectively these findings confirm the validity of the tool for measuring power on several common resistance training lifts. This outcome confirms Hypothesis 6 that the optical encoder is a valid tool of measuring power during free-weight resistance training activities in highly trained junior basketball players.

8.2.2 Changes in kinetics with fatigue

Continuous evaluation of power output with the optical encoder facilitated the investigation of changes that occur in bench press kinetics with repeated sets of high-intensity bench press training. A model of repeated sets of high intensity bench press training was employed in junior basketball players with a short but consistent history of resistance training. Previous research investigating bench press kinetics has evaluated the effects of progressively heavier loads on four phases of the concentric movement, including the 'acceleration phase', 'sticking region', 'maximum strength phase', and 'deceleration phase' [95, 318]. However these studies were somewhat limited in that only single repetitions on a small number of subjects were evaluated, given the very labour-intensive process of data collection and analysis with video. The results of this study confirm earlier reports of declining mean power output and peak power output in three of the four phases of the bench press as subjects approached repetition failure. Of particular interest was that the lowest power during the so-called 'sticking point' reached critically low levels (i.e. <5% of initial power) only after the peak power of the initial acceleration phase decreased by 30 to 60%. Therefore, Hypothesis #7 was accepted in that each phase of the concentric movement of the bench press movement will show substantial decreases in power output as consecutive bench press repetitions are performed. Such a finding is important in elucidating the cause of repetition failure by demonstrating that the first phase of the bench press movement is important in generating sufficient momentum to continue through the sticking point; once power declines substantially in the first phase, repetition failure in the second phase becomes probable.

Power production during the second and third phases of the bench press appears largely dependent on voluntary activation of cross-bridge cycling of the active muscle groups. This dependence on the voluntary cross-bridge cycling would make these phases sensitive to fatigue relative to the first phase, eliciting subsequent power development via the stretch-shortening cycle [96]. Once the components of the stretch-shortening cycle begin to fatigue, power loss in the sticking point is dramatic and repetition failure occurs. Therefore, if repetition failure at the sticking point is at least partially a result of declining power in the first phase, an athlete could complete more repetitions against a greater resistance if they were more fatigue resistant in the first phase. In order to stimulate fatigue in the first phase, and thus force adaptation, it would be necessary to train to the point of repetition failure. Resistance training programs not involving training to repetition failure would not elicit the same level of adaptation in the first phase because fatigue of the first phase did not become apparent until the subject approached repetition failure. By forcing adaptation in the first phase an athlete will be able to generate sufficient power to push through the sticking point against a greater resistance. The findings from this thesis implicate training to repetition failure as an important stimulus for eliciting adaptations in the initial acceleration phase of the bench press movement.

8.2.3 Bench press training to repetition failure

To test Hypothesis #8 that training to the point of repetition failure would elicit a greater improvement in bench press strength than a program not involving failure, two bench press programs were equated for training time (13 min, 20 s), intensity (80-105% 6RM), and volume (24 total repetitions). One group training with longer work intervals (4 x 6, sets x repetitions) regularly reached repetition failure. In contrast, the group training with shorter work intervals (8 x 3) were able to complete all prescribed repetitions. The 4 x 6 group with repetition failure had significantly greater strength and power improvement over the 8 x 3 non-failure group (6RM improvement: 7.3 kg versus 3.6 kg respectively; bench press throw mean power: 41 W versus 25 W, respectively, Chapter 6). Therefore, Hypothesis #8 that training to the point of repetition failure will improve bench press strength more than a program not involving failure was accepted. Since activating and overloading a high number of motor units is important to facilitate strength development [281, 304], the repetition failure group experienced greater strength gains presumably as a result of maximizing the recruitment of active motor units [200]. The maximized recruitment appeared to be particularly evident in the first and second phase of the bench press movement. These findings clearly support the concept that repetition failure training is an effective form of resistance training.

8.2.4 Bench press training involving forced repetitions

The purpose of the final study of this thesis was to investigate the value of repeated sets of training to repetition failure further contribute to strength, power, and hypertrophic gains [288]. No studies have investigated whether performing multiple sets of forced repetitions enhances muscular strength adaptation [288], though anecdotal support exists for the number of forced repetitions to be performed typically ranges from one to four [50, 89, 271, 309]. The final study tested Hypothesis #9 that additional volume of forced repetitions would convey no further benefit to strength development than ceasing training at the point of repetition failure. This approach involved a modification to the training program used in the previous bench press study comparing failure with non-failure training. The duration of the bench press training session was shortened to 8: 45 (min:sec) and an additional high volume group was added, training 12 x 3 in 13:40, thereby inducing repetition failure in all groups. The 4 x 6 and 12 x 3 groups not only failed by the end of every training session, but performed an average of four and three additional forced repetitions per training session, respectively. In comparison, the 8 x 3 group also reached repetition failure by the end of every training session, but performed an average of less than two forced repetitions per training session.

Despite having groups designated as high volume/high failure (12 x 3), low volume/high failure (4 x 6), and low volume/low failure (8 x 3), there were no substantial differences in the development of 6RM or 3RM strength, bench press throw for power, or muscle mass development between groups. Therefore, coaches and athletes should be advised that there is no additional benefit in the development of strength or power in training with a higher volume of forced repetitions. It should be noted however, this study did not evaluate very high volumes of overall training (>36 repetitions per exercise) or very high volumes of forced repetitions (>4 forced repetitions) that may be a part of some individual's programs. Very high total training volumes were not included in this research, nor were very high volumes of forced repetitions, because such programs are not supported in the literature [50, 236, 249] or industry recommendations [89, 271, 309].

8.2.5 Conclusions

This thesis has explored resistance training methods in actively training elite junior team-sport athletes to clarify the value of forced repetitions for maximising strength development. High intensity strength and power training in the 3 and 6RM range to the point of repetition failure was shown to be a more effective method to improve strength attributes than training in the same RM range but not to the point of repetition failure. These results have particular value to Australian basketball players given evidence of declining player body mass and fitness in some junior programs. However there is clearly substantial potential for individual players to improve these characteristics. When utilising resistance training, this thesis illustrates the greatest improvements were made in training to the point of repetition failure over non-failure training (10% versus 5% improvement in 6RM). However a greater number of forced repetitions did not lead to greater strength development (6% improvement in 6RM regardless of the volume of forced repetitions). While Basketball Australia has not traditionally tested measures of strength in their routine fitness testing, there is clear value in using strength training to improve results in tests of body size and power.

While the findings of this thesis support the use of maximal-intensity resistance training methods in junior team sport players, it is important to note that principles of periodizing an athlete's overall training program still apply [49]. Strength and conditioning coaches are well aware that training at high intensities for prolonged periods of time can result in athlete burn-out, injury, and overtraining syndrome [292]. Varying training intensity over the different cycles of an athlete's annual plan is an important part of strength development [24, 122, 250]. The strength training intervention studies of this thesis were conducted during the 'maximal strength' mesocycle of each team's periodised programs in the lead-up to major competitions (e.g. 2003 Junior World Basketball Championships, qualifying rounds for the 2004 Athens Olympic Games in volleyball). The 'maximal strength' mesocycle should continue to represent only a single portion of a team sport athlete's overall player development. However, it appears this phase of training is important for transfer of maximal strength into power development.

This thesis concludes that the maximal strength phase of a resistance training program for team sport athletes should include a mesocycle of resistance training to repetition failure. Strength and power gains should be enhanced by training to the point of repetition failure, but additional forced repetitions are unlikely to be of benefit.

8.3 Future Directions

The main direction for further research is to investigate the use of different amounts of fatigue and failure in lower body resistance training. The research within this thesis has demonstrated the value of training to the point of repetition failure in upper body resistance training to develop strength and power in highly trained junior basketball players. The next progression of this research is to implement a squat training program using the 4x8 versus 8x3 training programs to investigate if similar differences exist between these training programs in lower body training as exist in upper body training programs. Additional dependent variables should also be investigated to elucidate potential benefits of repetition failure training in tests specific to basketball such as sprinting and jumping. Such a lower body training study would require a lager number of athletes to participate than were available for this thesis. A larger sample of athletes would ensure a sufficient number of athletes completed the training and were available for testing, in light of the high subject mortality that could likely occur due to chronic and acute injuries sustained during routine basketball training. A lower body training study would also require that subjects were out of their competitive season and had only limited team commitment in order to reduce the confounding effects of chronic and acute fatigue from hectic competitive and travel schedules. To recruit a larger sample of players with a less demanding schedule would likely require study participants of a lower standard than those participating in the studies of this thesis.

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APPENDIX A – RAW DATA FOR STUDIES 1 & 2

The volume of data output produced by the mathematical models used in these studies makes presenting the raw data impractical.

APPENDIX B – RAW DATA FOR STUDY 3

B.1 Mean Power (reference: Figure 5.4)

	Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7
Rep1 (W)	309.2	304.9	303.3	346.1	312.0	395.7	423.2
Rep2 (W)	370.6	415.2	285.5	339.8	418.0	386.2	392.5
Rep3 (W)	353.5	392.1	300.5	332.6	415.2	369.0	396.9
Rep4 (W)	309.1	336.2	268.3	307.5	404.7	338.4	430.6
Rep5 (W)	316.7	269.1	232.2	272.2	367.3	336.1	405.6
Rep6 (W)	229.4	251.3	140.2	254.3	243.6	274.7	354.9
Rep7 (W)	346.7	375.5	317.8	377.1	332.7	353.6	402.3
Rep8 (W)	424.8	410.5	356.8	353.4	333.7	359.3	432.7
Rep9 (W)	362.9	370.5	357.3	381.4	310.7	351.4	430.2
Rep10 (W)	358.7	319.5	346.2	323.0	290.0	353.6	391.7
Rep11 (W)	380.4	243.6	264.1	310.6	282.3	310.8	426.5
Rep12 (W)	244.4	207.6	269.3	243.1	207.4	304.0	332.3
Rep13 (W)	314.6	384.7	296.1	358.4	316.7	364.4	382.4
Rep14 (W)	241.4	441.4	219.0	399.7	360.2	349.8	466.4
Rep15 (W)	213.8	383.3	252.5	353.5	315.0	321.2	535.6
Rep16 (W)	190.8	322.6	224.2	292.3	288.3	301.9	475.9
Rep17 (W)	138.1	260.1	197.9	238.0	222.2	272.6	385.0
Rep18 (W)	128.1	191.7	155.6	214.6	164.3	207.6	346.8
Rep19 (W)	236.0	186.9	269.5	233.6	318.3	272.1	379.3
Rep20 (W)	204.3	355.5	228.6	236.6	288.1	261.3	361.0
Rep21 (W)	160.9	345.3	197.0	189.5	288.7	203.2	327.2
Rep22 (W)	108.3	308.1	164.0	155.6	224.1	175.7	245.4
Rep23 (W)	129.3	174.4	101.3	71.6	141.3	104.0	207.9
Rep24 (W)	120.0	144.6	125.6	126.5	154.0	95.4	185.4

B.2 Peak power, first phase (reference: Figure 5.5)

	Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7
Rep1 (W)		354.3	346.5	371.7	356.6	357.1	
Rep2 (W)		337.9	370.0	399.9	340.0	409.7	283.4
Rep3 (W)		343.2	370.3	431.7	332.0	382.1	289.3
Rep4 (W)	310.0	352.4	354.9	436.8	280.3	364.4	292.7
Rep5 (W)	387.8	302.1	350.1	391.0	276.9	317.8	303.9
Rep6 (W)	338.9	323.3	296.0	289.2	157.5	320.3	253.7
Rep7 (W)		354.3	346.5	436.8	356.6	398.5	
Rep8 (W)		337.9	370.0	453.9	259.4	395.2	340.3
Rep9 (W)		375.8	405.5	494.3	223.9	379.8	311.3
Rep10 (W)	317.3	293.4	366.7	442.0	237.8	327.5	329.0
Rep11 (W)	349.1	295.6	366.4	399.3	171.7	370.1	324.9
Rep12 (W)	319.4	364.9	338.5	403.7	153.9	372.3	251.7
Rep13 (W)		354.2	346.8	388.0	237.8	373.4	323.0
Rep14 (W)	356.1	376.8	458.3	412.1	197.4	443.4	319.7
Rep15 (W)	452.0	407.2	443.8	402.5	221.1	355.2	296.8
Rep16 (W)	415.4	420.1	438.1	372.0	181.2	388.6	351.8
Rep17 (W)	340.6	345.9	346.0	412.8	195.3	368.2	380.8
Rep18 (W)	390.1	361.0	325.9	431.0	208.9	336.8	353.4
Rep19 (W)	330.8	382.2	337.3	355.3	217.7	419.0	404.7
Rep20 (W)	424.7	388.2	412.1	361.3	161.8	456.9	295.6
Rep21 (W)	410.9	318.2	378.8	382.9	150.0	379.2	385.3
Rep22 (W)	405.9	177.1	285.3	361.4	143.2	333.4	291.5
Rep23 (W)	205.6	140.5	163.1	238.9	98.8	204.7	172.1
Rep24 (W)	191.6	140.5	127.8	215.4	74.4	154.5	160.0

B.3 Low power, second phase (reference: Figure 5.6)

	Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7
Rep1 (W)		289.9	333.7	348.1	340.0	340.0	
Rep2 (W)	249.6	301.1	320.0	324.4	330.0	330.0	
Rep3 (W)	227.5	242.2	306.6	321.9	309.9	320.0	
Rep4 (W)	202.8	205.1	228.8	273.5	299.8	301.1	299.8
Rep5 (W)	178.1	121.4	195.0	102.1	284.4	281.8	298.9
Rep6 (W)	127.3	79.8	28.4	124.1	227.8	238.6	304.7
Rep7 (W)		327.9	290.0	321.0	299.0	287.6	
Rep8 (W)	264.5	301.6	248.0	296.3	322.4	278.1	
Rep9 (W)	265.6	253.9	177.9	327.2	264.0	271.5	
Rep10 (W)	206.6	202.3	192.0	251.8	471.1	260.2	301.7
Rep11 (W)	189.1	146.3	116.4	243.1	233.8	230.8	325.9
Rep12 (W)	120.6	96.3	103.0	202.7	184.9	203.3	206.4
Rep13 (W)	253.2	276.5	200.0	239.9	321.8	284.0	
Rep14 (W)	190.0	270.6	144.5	201.7	308.3	239.9	304.5
Rep15 (W)	161.4	199.4	112.6	199.6	282.4	191.7	339.2
Rep16 (W)	119.8	130.9	132.9	139.3	224.7	168.5	264.2
Rep17 (W)	148.2	61.2	113.6	60.9	163.8	141.8	162.0
Rep18 (W)	133.9	48.5	96.2	71.1	114.1	125.6	167.2
Rep19 (W)	174.5	284.6	167.6	154.5	309.0	197.4	330.8
Rep20 (W)	74.4	236.1	123.6	160.7	245.7	141.0	296.0
Rep21 (W)	98.4	149.6	115.3	141.9	235.0	140.3	253.7
Rep22 (W)	86.4	84.6	92.3	105.9	56.8	103.9	191.6
Rep23 (W)	-22.2	-17.5	60.7	-6.0	-73.7	-10.7	75.2
Rep24 (W)	-10.3	-44.0	47.4	69.0	-40.4	-45.9	27.8

B.4 Peak power – third phase (reference: Figure 5.7)

	Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7
Rep1 (W)	518.3	531.2	445.0	488.2	432.3	432.4	390.4
Rep2 (W)	524.2	552.9	507.4	430.7	426.5	466.8	374.6
Rep3 (W)	511.4	531.5	482.1	439.7	456.8	432.8	271.4
Rep4 (W)	505.2	481.1	503.1	390.8	402.8	416.3	276.8
Rep5 (W)	435.9	535.8	485.6	265.9	329.0	358.2	223.1
Rep6 (W)	383.3	408.4	289.7	305.9	291.1	335.4	160.0
Rep7 (W)	513.3	418.9	457.7	506.8	651.5	523.6	371.0
Rep8 (W)	563.4	480.1	465.4	487.4	538.2	538.4	330.3
Rep9 (W)	491.0	452.2	455.2	536.1	475.9	463.6	285.1
Rep10 (W)	482.1	384.0	417.1	477.9	426.7	412.1	344.6
Rep11 (W)	441.9	406.0	456.5	471.9	443.5	263.0	244.3
Rep12 (W)	267.9	325.9	361.5	270.3	325.9	225.5	198.6
Rep13 (W)	581.7	500.6	450.0	420.3	528.8	486.7	423.4
Rep14 (W)	502.1	485.5	498.2	412.6	457.3	436.1	326.1
Rep15 (W)	398.8	379.7	436.1	342.3	471.3	354.7	310.9
Rep16 (W)	474.2	256.1	469.2	369.6	356.4	271.9	238.8
Rep17 (W)	274.5	222.2	385.6	326.1	269.6	260.2	264.9
Rep18 (W)	306.7	171.8	317.1	236.1	255.4	248.0	156.4
Rep19 (W)	552.1	320.5	447.5	398.0	397.0	424.4	341.7
Rep20 (W)	556.5	294.1	454.7	373.3	386.5	440.3	263.5
Rep21 (W)	498.9	185.4	438.8	350.7	323.4	349.4	185.5
Rep22 (W)	334.6	200.4	337.0	241.2	222.0	272.2	109.0
Rep23 (W)	274.5	133.3	234.6	153.5	252.6	189.6	128.0
Rep24 (W)	189.5	116.3	265.0	158.7	330.8	250.4	154.8

B.5 Criterion (Video) versus Practical (Gymaware) Power Output (reference: Table 5.1)

	Bench press - max concentric		Bench press - max eccentric		Bench press - mean concentric		Bench press - mean eccentric	
	Video	Gymaware	Video	Gymaware	Video	Gymaware	Video	Gymaware
Subject 1 (W)	616.55	634.61	653.06	686.12	248.44	254.38	400.98	407.00
Subject 2 (W)	552.17	578.85	596.80	622.37	306.86	317.00	337.00	356.00
Subject 3 (W)	285.73	288.16	576.63	594.93	184.11	187.74	398.93	402.00
Subject 4 (W)	284.65	286.46	281.33	289.46	245.56	245.59	194.10	198.58
Subject 5 (W)	519.54	519.51	586.25	613.00	303.32	317.80	338.22	347.16
Subject 6 (W)	468.76	489.39	684.07	699.15	233.61	243.65	344.92	338.14
Subject 7 (W)	339.99	348.90	533.18	560.97	226.66	235.21	343.24	349.00
Subject 8 (W)	360.94	378.32	405.22	421.65	246.44	250.95	229.70	234.16
Subject 9 (W)	444.35	426.20	553.40	589.54			337.52	352.07

	Squat - max concentric		Squat - max eccentric		Squat - mean concentric		Squat - mean eccentric	
	Video	Gymaware	Video	Gymaware	Video	Gymaware	Video	Gymaware
Subject 1 (W)	696.86	670.10	449.49	453.00	241.06	241.50	244.41	251.06
Subject 2 (W)	842.88	835.50	566.01	571.79	418.69	423.74	286.96	292.74
Subject 3 (W)	527.10	507.34	430.64	442.29	288.79	292.53	238.72	240.79
Subject 4 (W)	1168.10	1193.82	958.74	956.30	512.64	511.85	434.14	447.11
Subject 5 (W)	298.92	298.86	273.37	279.80	215.72	218.63	177.84	184.58
Subject 6 (W)	649.83	653.67	641.68	657.12	416.63	424.52	324.00	326.65
Subject 7 (W)	1020.13	1023.21	938.70	910.87	512.93	514.32	536.14	544.42
Subject 8 (W)	851.85	845.00	588.31	592.50	361.35	357.00	398.69	411.60

	Throw - max concentric		Throw - mean concentric	
	Video	Gymaware	Video	Gymaware
Subject 1 (W)	721.97	727.50	411.26	394.50
Subject 2 (W)	798.01	785.87	386.38	376.31
Subject 3 (W)	801.97	789.90	398.18	405.38
Subject 4 (W)	793.69	826.90	349.43	358.49
Subject 5 (W)	656.45	653.04	354.83	344.70
Subject 6 (W)	984.91	1000.27	418.58	433.29
Subject 7 (W)	549.70	536.34	304.24	297.79
Subject 8 (W)	701.55	692.50	424.02	412.62
Subject 9 (W)	702.17	692.32	332.49	335.63
Subject 10 (W)	556.17	559.60	316.93	312.34

APPENDIX C – RAW DATA FOR STUDY 4

C.1 Fitness Tests (reference: Figure 6.1 and 6.2)

8x3 Group	6RM Strength (kg)		Throw Power (W)	
	Pre	Post	Pre	Post
Subject 1	72.5	75	374	388
Subject 2	70	80	380	414
Subject 3	85	85	433	433
Subject 4	72.5	77.5	408	395
Subject 5	65	70	337	357
Subject 6	60	65	325	365
Subject 7	60	60	285	334
Subject 8	60	60	257	286
Subject 9	75	80	412	445
Subject 10	60	65	274	320
Subject 11	62.5	65	287	310
4x6 Group				
Subject 12	72.5	80	409	462
Subject 13	95	105	492	486
Subject 14	72.5	75	372	427
Subject 15	80	85	402	419
Subject 16	72.5	80	387	430
Subject 17	67.5	75	298	341
Subject 18	65	72.5	298	323
Subject 19	70	80	334	396
Subject 20	77.5	82.5	382	398
Subject 21	70	75	371	398
Subject 22	57.5	65	305	328
Subject 23	67.5	75	331	377
Subject 24	62.5	70	270	361
Subject 25	55	67.5	277	338
Subject 26	55	62.5	228	284

APPENDIX D – RAW DATA FOR STUDY 5

D.1 Fitness Tests (reference: Table 7.3 and Figure 7.1)

Subject	Group	6RM (kg)		3RM (kg)		Throw (peak, W)		Throw (mean, W)		Chest circumference (cm)		Fat Mass (kg)		Muscle Mass (kg)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
s1	12x3	82.5	87.5	90	90	564.4	629.4	299.6	334.1	102.3	104.1	8.0	8.1	43.9	45.0
s2	12x3	80	95	85	90	679.3	750.0	323.5	350.0	107.3	109.1	8.3	7.8	45.1	46.3
s3	12x3	75	77.5	80	82.5	537.3	490.7	284.7	310.4	111.5	113	11.2	11.4	55.8	56.9
s4	12x3	80	90	87.5	92.5	631.4	761.7	330.6	383.8	104.7	104.2	9.4	8.2	48.6	49.0
s5	12x3	55	57.5	62.5	65	501.7	477.8	331.6	250.9	105.7	108.2	12.7	13.4	44.0	44.1
s6	12x3	82.5	85	87.5	92.5	650.2	757.9	332.8	410.2	100.5	101.2	6.7	6.7	44.2	44.8
s7	12x3	62.5	65	65	75	546.8	573.8	289.3	305.4	100.9	102	6.7	6.6	42.1	41.9
s8	12x3	82.5	92.5	90	100	669.2	829.7	356.6	399.7	106.6	107.5	9.2	9.5	44.5	46.2
s9	4x6	80	80	85	85	551.2	481.8	336.7	294.8	105.4	105	6.0	6.0	38.8	39.1
s10	4x6	82.5	87.5	90	92.5	625.9	724.5	323.6	362.0	107	108.9	8.9	8.1	46.3	47.7
s11	4x6	80	85	85	90	642.1	702.4	318.0	368.0	101.4	101.4	8.6	7.5	41.3	42.5
s12	4x6	70	72.5	77.5	80	563.8	635.6	308.2	400.0	106.8	107.9	7.1	6.9	42.2	42.7
s13	4x6	82.5	90	87.5	95	707.9	754.7	468.5	423.7	111.6	111.6	9.7	9.8	53.2	54.3
s14	4x6	77.5	80	85	87.5	534.1	541.2	323.8	304.9	101.2	100.7	6.0	6.1	40.0	40.4
s15	4x6	67.5	72.5	70	75	455.6	577.3	263.7	301.7	93.8	95.5	6.7	6.2	37.4	37.9
s16	8x3	80	87.5	90	100	758.2	715.7	344.3	399.2	107.2	105.6	8.9	7.8	41.7	42.2
s17	8x3	82.5	87.5	87.5	90	664.5	652.0	337.3	359.8	107.3	106.2	8.0	7.5	52.8	51.9
s18	8x3	70	72.5	77.5	80	410.0	628.0	301.6	311.8	101.5	100.2	8.9	8.4	40.4	40.5
s19	8x3	85	90	87.5	95	593.6	726.9	360.6	382.0	107.5	108	11.5	11.7	51.1	51.3
s20	8x3	55	57.5	57.5	62.5	407.5	403.6	227.1	239.2	98	97.5	6.6	6.5	40.5	41.2
s21	8x3	85	90	90	97.5	765.5	875.3	381.6	417.6	109	109.5	8.1	8.0	54.2	55.2
s22	8x3	72.5	72.5	75	75	492.7	521.6	270.7	311.9	99.7	100.5	9.8	10.0	46.1	47.4

D.2 Failure and Training Compliance Rates (reference: Table 7.4)

Subject	Group	Mean of missed reps per day over study (reps)	Compliance (%)
s1	12x3	4.3	78
s2	12x3	4.0	78
s3	12x3	2.5	72
s4	12x3	3.9	72
s5	12x3	4.5	78
s6	12x3	2.5	72
s7	12x3	3.7	83
s8	4x6	3.4	67
s9	4x6	4.1	78
s10	4x6	3.6	78
s11	4x6	4.7	83
s12	4x6	4.3	89
s13	4x6	4.4	78
s14	4x6	6.2	94
s15	8x3	2.2	72
s16	8x3	1.4	78
s17	8x3	2.2	78
s18	8x3	1.8	77
s19	8x3	3.0	77
s20	8x3	1.5	83
s21	8x3	2.0	83

D.3 Total Concentric Duration per Training Session (reference: Table 7.4)

Subject	Group	Concentric Duration (s)
s1	4x6	36.83
s2	4x6	38.81
s3	4x6	35.69
s4	4x6	38.49
s5	4x6	38.76
s6	4x6	47.52
s7	4x6	50.54
s8	12x3	71.93
s9	12x3	54.17
s10	12x3	61.94
s11	12x3	50.83
s12	12x3	56.20
s13	12x3	49.68
s14	12x3	58.31
s15	12x3	71.45
s16	8x3	41.54
s17	8x3	43.01
s18	8x3	34.77
s19	8x3	55.21
s20	8x3	41.42
s21	8x3	37.37
s22	8x3	31.48

D.4 Total Work Performed per Training Session (reference: Table 7.4)

Subject	Group	Total Work (J)
s1	4x6	13748
s2	4x6	17742
s3	4x6	14659
s4	4x6	13981
s5	4x6	17461
s6	4x6	16872
s7	4x6	21480
s8	12x3	28312
s9	12x3	25208
s10	12x3	21770
s11	12x3	27093
s12	12x3	30510
s13	12x3	26116
s14	12x3	26514
s15	8x3	12669
s16	8x3	19718
s17	8x3	16981
s18	8x3	16319
s19	8x3	13096
s20	8x3	18891
s21	8x3	17834

D.5 Mean power per training session (reference: Table 7.4)

Subject	Group	Power (W)
s1	4x6	230.2
s2	4x6	284.2
s3	4x6	263.2
s4	4x6	207.1
s5	4x6	254.4
s6	4x6	231.5
s7	4x6	200.9
s8	12x3	317.5
s9	12x3	258.7
s10	12x3	220.1
s11	12x3	332.1
s12	12x3	340.4
s13	12x3	264.7
s14	12x3	211.2
s15	12x3	208.6
s16	8x3	290.7
s17	8x3	294.6
s18	8x3	234.4
s19	8x3	216.3
s20	8x3	318.1
s21	8x3	344.6

APPENDIX E – UNSUCCESSFUL SQUAT TRAINING STUDY – ASSESSMENT OF SQUAT RESISTANCE TRAINING PROGRAM CONFIGURATION ON DEVELOPING STRENGTH AND COURT-SPECIFIC POWER

E.1 Preface

This appendix details an experimental study examining the transfer of two different squat resistance training program configurations to changes in squat strength and routine fitness tests of vertical jump and sprinting. Unfortunately the study can only be considered a pilot study considering the high drop out rate and level of fatigue of subjects for the post-training fitness testing, and is therefore not included in the body of this thesis. However the outline of the study is presented here as the preliminary findings of applying previously displayed upper body (bench press) principles to lower body training. The preliminary findings also provide some directions for future investigations.

E.2 Introduction

There is a long-held belief among sport coaches that strength training programs involving slow contraction speeds result in slow execution of sport-specific skills [305]. Recent empirical evidence lends support to this observation by illustrating the specificity of training power output and velocity [182]. However, the majority of this research involves untrained subjects [231] performing single joint [254], isometric [165] or isokinetic training [31]. Single-joint, isometric and/or isokinetic training programs are effective in maintaining a high degree of experimental control [165], while studying untrained subjects maintains participation rate by avoiding the relatively high incidence of injury [283] and accumulated fatigue [176]. There are however different responses to resistance training depending on the training history of the subjects [249] and the training modality used [86, 170]. Therefore, there is some question regarding the validity and transfer of the findings of much of the published research advocating velocity-specific resistance training to actively training athletes.

More recent research on velocity-specific training shows that heavy resistance training combined with sport-specific skills can increase power output of sports-related skills such as throwing [75, 208], kayaking [196], jumping [160], and sprinting [44, 80].. The benefits of heavy resistance training are likely derived from improving force production necessary in the initial few metres after a stationary start as the athlete overcomes their own inertia. Resistance training increases force output while sport-specific training maintains velocity, thereby improving overall power output [196, 212]. In the absence of sport-specific training however, the traditionally held view of velocity specificity holds true [122].

Previous thesis chapters demonstrated that highly fatiguing bench press training to the point of repetition failure enhances upper body strength and power development over an equal-volume program involving a lower level of fatigue. However, since the physiological responses to different forms of resistance training depend on variables such as muscle fibre composition, size of muscle groups involved, and number of joints involved in the lift [182] it is not clear if this repetition failure training applies to sport-specific tests of power after lower body training. Therefore, this thesis also sought to determine whether training to failure also improves lower body strength and power in team sport athletes. The purpose of this investigation was to determine whether a highly fatiguing squat training program enhances lower-body strength and sport-specific power development to a greater degree than an equal-volume program with less fatigue.

E.3 Methods

E.3.1 Subjects

Subjects were 13 highly trained male junior basketball players (age 18.6 ± 0.3 y, height 200.3 ± 10.6 cm, mass 90.7 ± 11.6 kg, mean ± SD). Subjects provided written consent for testing as part of their scholarship arrangements with the Australian Institute of Sport (AIS), in accordance with requirements of the Ethics Committee of the AIS. Testing and training procedures were explained prior to the start of the study and subjects were informed that they could withdraw at any time without prejudice.

E.3.2 Overview of Experimental Design

Each subject undertook a series of muscle strength and power tests, before and following a six-week lower body strength training intervention. Strength tests comprised the Smith Machine back squat 6 repetition maximum (6RM) and 3 repetition maximum (3RM); power tests were a 20-m sprint test, countermovement vertical jump height, and the maximal power generated during 20kg, 30kg, and 40kg Smith Machine jump squats. Body composition was evaluated with a series of anthropometric measures. While most of the athletes departed on international tours immediately after the post-training testing session, four athletes remained available one week later and were re-tested after one week of no resistance training.

After pre-training testing, subjects were matched for 6RM squat and training age for squats. The training age, defined as the length of time each subject had been on a regimented resistance training program for squats, was based on each athlete's individual weight-room record. Subjects were then assigned to one of three squat training groups comprising either 4x6 or 8x3 (sets x repetitions). Both groups trained an equal number of repetitions (24 total repetitions) at the same relative intensity of their six repetition maximum (85 – 100%) in an equal amount of time (8 min, 20 s), two times per week for six weeks. After six weeks of training all subjects were re-tested and evaluated for change in 6RM, 3RM, 20-m sprint time, countermovement vertical jump height, 20kg, 30kg, and 40kg Smith Machine jump squats peak power, and body composition. To verify that expected differences in work, power, and concentric time between groups were present, movement kinetics for each repetition of every subject were measured with GymAware™ optical encoders (Kinetitech Performance Technology Pty Ltd, Canberra, Australia).

E.3.3 Anthropometric Measures

Stretched height was measured during inspiration using a stadiometer (Holtain Ltd. Crymych, Dyfed). The typical error of measurement (TEM) for measuring height, including biological variation, was typically not more than 1% [229]. Beam balance or digital scales were used to measure body mass to the nearest 0.1 kg with a TEM between days, including biological variation, of 1% [229]. Skinfolds comprised the sum of seven skinfold thicknesses from triceps, subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf measured with Harpenden calipers (British Indicators Ltd., West Sussex, United Kingdom), with a TEM of the current anthropometrist of <2% [229].

Fractionation of body composition was used to partition total body mass into four different constituent compartments: fat mass, residual mass, muscle mass and bone mass according to methods outlined previously [319]. The anthropometric profile consisted of the following measurements: height, mass, seven skinfolds, eleven girths, eight lengths, and eight breadths. The four compartment masses were estimated individually by measuring a representative subset of lengths, breadths and girths scaled for a known height and mass. The percent muscle mass was derived as the percentage of estimated muscle mass to the estimated total body mass. The TEM values of the current anthropometrist for estimating the fractionation components were: fat mass (0.1 kg, 1.4%), residual mass (0.2 kg, 0.9%), bone mass (0.2 kg, 1.3%), muscle mass (0.2 kg, 0.7%), and % muscle mass (0.2%, 0.5 %). The same anthropometrist conducted all measurements both pre- and post-training.

E.3.4 6RM and 3RM Squat Testing

Squat testing was conducted with a Smith Machine (Life Fitness, Victoria, Australia) consisting of a horizontal barbell mounted on two vertical rails thereby keeping the bar level and allowing it to move only in the vertical plane. The technical criteria for squats has been previously documented [89]. Briefly, the bar was supported on the back in either the ‘high-bar’ or ‘low-bar’ positions, with the feet shoulder-width apart and knees slightly flexed. The hips and knees were slowly flexed until the top of the thighs were parallel with the floor. The hips and knees were then extended to return to the starting position. The back remained flat and the heels of the feet remained on the floor. The bar was not permitted to stop at any point throughout the lift. Failing to meet any of these technical criteria constituted an unsuccessful attempt.

Previously documented training records were used as a guide for selecting the first test mass. The mass was then progressively increased with each successful set of 6 or 3 repetitions by an amount self selected by the subject (typically 5 kg) with a minimum of 180 s rest between attempts. Prior to testing, each subject completed a thorough warm-up involving 10 min of stationary cycling and three sets of squats comprising 12 repetitions at 40kg, 6 repetitions at 60kg, and 3 repetitions at 70kg with 2-min rest between sets.

E.3.5 Jump Squat Power

Subjects were evaluated for peak power output during a 20kg, 30kg, and 40kg Smith Machine jump squat measured on an optical encoder. Subjects performed two sets of two jump squats at each load in a Smith Machine for a total of twelve jumps. The peak power output was recorded for each jump.

E.3.6 Sport-Specific Court Tests

Two maximal effort tests were used to measure sport-specific power: 20-m sprint time and vertical jump height [284]. For the 20-m sprint test, the fastest of three attempts of elapsed movement time from a stationary standing start to a 20-m point was recorded using electronic light gates (SWIFT Performance Equipment, Lismore, Australia). Splits were measured at 5-m, 10-m and at 20-m. The elapsed time between the 10-m and 20-m splits was later calculated for a 'flying 10-m' time. A vertical jump test measured the best of three maximal counter-movement jump heights allowing a single backward step using a Vertec vertical jump apparatus (SWIFT

Performance Equipment, Lismore, Australia). Athletes had performed these tests many times prior to testing so a minimal learning effect was assumed.

E.3.7 Training Analysis

A Gymaware™ sensor was used for continuous monitoring of all repetitions during training for total work, concentric duration, and mean concentric power. From these measures, the total work, concentric duration, and mean concentric power performed by each group were confirmed. The Gymaware sensor consisted of a spring powered retractable cord that passed around a pulley mechanically coupled to an optical encoder, with the end of the cord attaching to the barbell. The device was positioned on the floor perpendicular to the movement of the barbell and measured velocity and displacement of the barbell. The device gives one pulse approximately every 3 mm of load displacement. Each displacement value is time-stamped with a 1 ms resolution. Position - time data points are generated at a maximum rate of 25 Hz. The entire displacement (mm) and time (ms) for the movement were used to calculate mean values for power.

A standardised 14 point Borg scale (6 to 20) was used to assess each athlete's perception of training intensity [79].

E.3.8 Training Program

Each group trained twice per week on Mondays and Thursdays over the six-week training block. The six-week training intervention corresponded with a strength training phase in the team's strength and conditioning program within their annual cycle.

Experimental groups trained either 4 sets of 6 repetitions with each set commencing every 2 min, 45 s (4x6, n=7) or 8 sets of 3 repetitions commencing every 1 min, 13 s (8x3, n=6). Both groups trained at the following intensities of their 6RM in each session: 90% for the first 25% of their sets, 95% for the next 25% of their sets, and 100% of their 6RM for the final 50%. Training sets of 3 or 6 were used to elicit different amounts of fatigue but no group consistently trained at 100% of their 3RM, only at 90-100% of their 6RM. As each subject's strength gradually increased over the duration of the study, the weights were systematically adjusted for the duration of the study. All training was directly supervised by the investigators to ensure quality and compliance of training.

Weights used in each session were rounded to the nearest 2.5 kg. Other weight room training by all groups involved 5-10 min stationary bicycling as warm-up, a traditional 60 min whole body routine involving all major muscle groups of the body, and 10 min stretching on cool-down. No other lifts in their training program specifically targeted similar muscle groups in a task-specific way to squats (e.g. front squats, hack squats, etc.), but the synergistic involvement of the quadriceps, gluteal group, and lower back during other lifts cannot be entirely be ruled out. Regardless, all athletes performed training programs based on the same design, so any additional effects would presumably affect all subjects. Other sport-specific training by the subjects involved daily team practices and skills sessions appropriate to elite junior level (i.e. international) players.

E.3.9 Statistical Analysis

All raw data are expressed as mean ± SD. Estimates of mean change and difference scores are expressed as mean with 95% confidence limits (CL) to establish the precision of the estimate. Scores of each test before and after training were analysed using a two-way ANOVA (testing occasion x group) with repeated measures. Subjects were required to have participated in a minimum of 80% of the training sessions to be included in the analysis. Kinematic data gathered from the optical encoders was analysed by one-way ANOVA for differences between groups. P-values were considered significant at $p<0.05$.

E.4 Results

A summary of test values before and after the six-week training intervention is shown in Table E.1. The subject mortality rate was particularly high in this study due to both chronic overuse injuries (e.g. Achilles and patellar tendonosis) and acute injuries (e.g. foot fracture) associated with regular basketball practice and competitive games. While 13 subjects began the study, only eight had participated in the required 80% of the training sessions by the end of the study and were free from injuries contraindicating participation in post-training testing. Of these eight, five were in the 4x6 group and three were in the 8x3 group.

Table E.1- Anthropometric, strength and power characteristics in team sport athletes before and after six-weeks of high intensity resistance training.

Test	Main effect of Training			
	Pre-training		Post-training	
	Mean	SD	Mean	SD
Anthropometry (n=9)				
Body Mass (kg)	90.78	11.64	92.08	11.56
gluteal thigh circumference (cm)	59.13	3.14	59.99	2.92
total muscle mass (kg)	43.43	43.43	44.14	5.93
muscularity (%)	46.7	1.2	47.1	1.2
Strength (n=7)				
6RM (kg)	99.6	20.5	120	19.7
3RM (kg)	112.9	19.5	135	17.6
Resisted CMJ, Peak power (n=8)				
20kg (W)	956	129	870	137
30kg (W)	1254	141	1151	146
40kg (W)	1500	181	1355	158
Court Tests (n=8)				
Countermovement Jump Height (cm)	331.8	10.4	332.4	9.7
Agility (s)	5.68	0.37	5.71	0.48
5-m sprint (s)	1.12	0.07	1.19	0.09
10-m sprint (s)	1.87	0.12	1.96	0.14
20-m sprint (s)	3.16	0.24	3.26	0.27
fly 10-m sprint (s)	1.29	0.11	1.3	0.14

E.4.1 Training Group Analysis

While all efforts were made to control for training volume, total work per training session was higher in the 8x3 group (884 J, 95%CL: 123 to 1645, p=0.03). Despite the higher total work, the difference between groups in mean concentric time per training set was a non-significant 0.65 s (95%CL: -1.0 to 2.3, p=0.40). More work being done in the same amount of time resulted in greater power for the 8x3 group (40.9 W, 95%CL: 7.7 to 74.1, p=0.02). Analysis of RPE revealed that the 4x6 group perceived significantly more exertion (18.7±0.8) than the 8x3 group (15.7±1.3) (p<0.01).

E.4.2 Anthropometry

Over the six-week training block, there were substantial increases in overall body mass (1.3 kg, 0.18 to 2.3 kg, $p=0.03$), gluteal thigh circumference (0.84 cm, 0.34 to 1.33, $p<0.01$), total muscle mass (0.66 kg, 0.17 to 1.14, $p=0.02$), and percent muscularity (0.36%, 0.16 to 0.56, $p<0.01$). There were no statistically significant differences in the changes made by each group, though the greater improvements made by the 4x6 group compared with the 8x3 group in muscle mass (0.96kg, -0.02 to 1.94, $p=0.06$) and muscularity (0.37%, -0.05 to 0.78, $p=0.07$) approached significance.

E.4.3 Strength Testing

There was a clear main effect of training with an increase in 6RM of 19.9kg (15.3 to 24.5, $p<0.01$) and 3RM of 21.9kg (17.1 to 26.7, $p<0.01$). There was no statistical differences in the magnitude of strength improvements between the training group on the 6RM ($p=0.13$) or the 3RM ($p=0.36$).

E.4.4 Power Testing

Peak power output was substantially lower during resisted countermovement jumps after training than before the six-week training intervention at all resistances. The magnitude of the decline at 20kg was 93 W (-163 to -22, $p=0.02$), 109 W at 30kg (-205 to -109, $p=0.03$), and 160 W at 40kg (-160 to -258, $p<0.01$). Power loss at each resistance equated to a loss of 8-9% of the pre-training value. There were no statistical differences between training groups (all $p\geq0.20$).

E.4.5 Court Tests

After six weeks of squat training, 20-m sprint time was significantly higher at the 5-m (0.07 s, $p<0.01$), 10-m (0.10 s, $p<0.01$), and 20-m splits (0.11 s, $p=0.01$) though the difference in flying 10-m sprint time was only 0.01 s ($p=0.84$). The increase of countermovement jump height (0.5 cm, -2.3 to 3.3) was not statistically significant ($p=0.76$). There were no statistical differences in court test results between training groups (all $p>0.35$).

One week after the post-training testing, four subjects were available for retesting. Analysis of the fitness testing results for these four subjects alone revealed that in the initial series of post-training testing there was a significant increase in 5- and 10-m sprint time (0.06 s, $p=0.04$) that was not significant one week later (<0.01 s, $p=0.92$).

E.5 Discussion

The main purpose of this study was to investigate the value of a relatively high intensity resistance training program on strength development and sport-specific power output. A variety of issues hindered this investigation, which illustrates some of the difficulties in conducting research involving high-performance athletes. In particular, the high incidence of both acute and overuse injuries in addition to the demands of elite competition precluded the successful execution of the post-training assessment of strength and power, rendering the study a relative failure.

The cohort of athletes involved in this investigation regularly trained in multiple team and individual training sessions per day. Total training volume for each athlete involved resistance training, individual skills and fitness training, and team practices were typically in excess of 20 hours per week. Maintaining such a high training volume and intensity has a high potential for leading to overuse injuries, even when the athletes are carefully monitored by a medical team of health professionals [283]. If an athlete in the current study began to show signs of overuse injury, the coaching staff would typically reduce the intensity and volume of resistance training. Consequently these athletes had to be removed from the current study to maintain standardization and adherence to experimental procedures. As a result of medical withdrawals, only 8 of the 13 athletes allocated to training groups at the commencement of the study completed both pre and post testing sessions and the required minimum amount of training. Of those completing all session, five were in the 4x6 group and three were in the 8x3 group. Group sizes of five and three unfortunately lacked the necessary statistical power to make any inferences about the differences between training groups.

While no definitive conclusions can be made about the differences between training programs, there is a substantial main effect that resistance training improved strength but caused a decrement in generation of power. Such an effect could arguably lead to questions about the effectiveness of athletes using resistance training to develop sport-specific power. However, the timing of the training intervention within the athletes' competition season is a confounding variable that appears to have played a substantial role in the outcomes. The current investigation was scheduled within a fixed window of eight consecutive weeks in the South-East Australian Basketball League (SEBAL) competition season. The subjects were not on tour and were scheduled to undertake a strength-development phase of training. While it is unusual for coaching staff to schedule a strength development phase during a competition phase, the scheduled departure of the athletes on an extended international tour immediately after the competition season necessitated this arrangement. For the current investigation to fit in this 8-week window of opportunity, the post-training test sessions fell immediately after a short, but intense multi-game road trip. While the obvious solution would be to delay the post-testing session for several days while the athletes recovered, testing on most athletes would not be possible again for many months to follow due to either injury or unavailability of subjects due to overseas commitments. As a result of the accumulated fatigue that results over a competition season [176], combined with the acute fatigue after several days of travel and competition, the results of the post-training testing cannot be directly attributed to the resistance training program. The selection of a control group from the team would have allowed conclusions about the main effects of a high-intensity resistance training program during the competition phase to be made, but the total number of subjects available was insufficient to draw three adequately sized groups. The purpose of this study was to compare different resistance training designs rather than the effects of including resistance training, so the inclusion of a control group was neither feasible nor necessary in the original design.

Several studies have attempted to quantify the effects of a generic in-season strength training program on strength and sport-specific power tests. The absence of strength training program during the in-season training has been associated with reductions in both speed and strength [62, 141], despite maintenance of body mass [47, 62, 141]. If the in-season training program involves resistance training, strength and running speed can be substantially improved [87, 139, 142]. Subjects experienced a 1.5% increase in total body mass and muscle and ~20% improvement in squat strength. In contrast to these improvements in morphology and strength a ~5% increase (impairment) in sprint time at the 5- and 10-m splits of a 20-m sprint, immediately after the completion of the season were observed. However, after one week of recovery, there was a reversal of impairment in the 5- and 10-m sprint times. While this analysis is under-powered with only four subjects, the initial decrease in explosive power may primarily be related to the acute fatigue of travel and competition rather than the strength training intervention. Such fatigue may have impaired explosive power, but would not have had similar effects on strength testing due to the rapid recovery of strength tasks after fatigue [310]. The recovery of 20-m sprint speed one week after the first session of post-training testing further supports the tentative conclusion that decrements in sprint speed were linked to acute fatigue. Future studies with adequate statistical power are necessary to fully address this question.

With the inclusion of an in-season resistance training program, substantial improvements can be made in gaining muscle mass and strength. Due to low statistical power and lack of a control group, the possibility that that such improvements would not have occurred without the resistance training program cannot be ruled out. However, it seems unlikely that strength and mass would improve without resistance training based on previous research [47, 62, 141]. Result indicate that impairment of power output is likely, but considering the context of the post-training testing, and the recovery of sprint speed after a week of rest, separating the accumulated fatigue of a competitive season from the strength training intervention is not possible. Therefore, care must be taken by researchers in drawing conclusions about the differential effects of an in-season training program on strength and power tests. Researchers must consider both the long term fatigue that accumulates as the competitive season progresses and short term fatigue after games and travel that the subjects are experiencing.