The Potential for Variable Range of Motion Training to Optimise Functional Performance

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Ross Allan Clark

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ABSTRACT

Although full range of motion (ROM) resistance training is a successful method of enhancing force potential, it does possess a number of limitations such as terminal deceleration and the countermovement occurring at the same position during all repetitions. In an effort to overcome these drawbacks, this thesis explored the effects of variable range of motion (VROM) resistance training on neuromuscular performance, activation and muscle architecture. This method of training involves the countermovement position occurring in a different ROM for each set. Experiment 1 consisted of a study examining the load lifted, force produced and concentric workload during a VROM training session. The findings of this study suggested that VROM training results in increased peak force levels as the training ROM decreased, a potential foundation for enhanced longitudinal performance benefits. A potential mechanism for these proposed gains in response to VROM training appeared to be a change in muscle architecture. Therefore, Experiment 2 examined the relationship between muscle architecture and upper body pressing strength and power in 30 professional rugby league players. The results of this study revealed that while changes in pennation angle were originally believed to be a potential mechanism for performance gains in response to VROM training, the limited relationship between this variable and function suggested otherwise. Finally, Experiment 3 examined the effect of VROM training on strength, power, neuromuscular activation and muscle architecture in 22 professional rugby league players. The results of this final study revealed that VROM training produced enhanced full ROM ballistic performance and isokinetic strength towards the terminal phase of the bench press movement. These findings suggest that a VROM training program provides superior performance gains in subjects with extensive resistance training experience, and is therefore a worthy addition to a high level athlete's training program.

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LIST OF ABBREVIATIONS

ABBREVIATION	DEFINITION
1RM	one repetition maximum
5RM	five repetition maximum
6RM	six repetition maximum
A	acceleration
ACSA	anatomical cross-sectional area
ANOVA	analysis of variance
AP	acceleration phase
APN	aponeurosis
ATP	adenosine triphosphate
cm	centimetres
CON	control
D	displacement
DP	deceleration phase
EMG	electromyography
EXP	experimental
EXT	extension
F	force
FASL	fascicle length
FFT	Fast Fourier Transform
FL	fascicle length
FLEX	flexion
ht	height
HWT	heavy-weight
Hz	Hertz
ICC	intra-class correlation coefficient
JS	joint stiffness
kg	kilograms
km	kilometres
LL	limb length
LSD	least significant differences
LWT	light-weight
m	metres
M	mass

ABBREVIATION	DEFINITION
mg	milligrams
MHz	megahertz
MIX	mixed
MPF	median power frequency
ms	milliseconds
MT	muscle thickness
MTH	muscle thickness
MWT	middle-weight
N	Newtons
n	number
OP	oscillation phase
P	power
PAN	pennation angle
PAR	partial
PB	personal best
PCSA	physiological cross-sectional area
PF	peak force
R	intra-class correlation coefficient
RF	rectus femoris
RFD	rate of force development
RMS	root mean squared
ROM	range of motion
RT	resistance training
s	seconds
S	sprint
SEM	standard error of measurement
SPSS	statistical processing software for students
SR	sticking region
SSC	stretch-shortening cycle
SD	standard deviation
TM	trademark
TTP	time to peak
U.S.A.	United States of America
ULT	ultrasound
VL	vastus lateralis
VROM	variable range of motion
W	work

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DECLARATION

I, Ross Clark, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Health and Human Performance, Central Queensland University, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Ross Clark

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August 2007

Publications

Peer Reviewed Journal Articles

Experiment 1: An Examination of Strength and Concentric Work Ratios During Variable ROM Training has been accepted for publication in a journal specific format by the Journal of Strength and Conditioning Research.

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Chapter 1

INTRODUCTION

1.1 The Potential of Variable Range of Motion Training

Dynamic power and strength are essential characteristics for athlete's attempting to reach the highest level of their chosen sport. Numerous studies have shown that strength and power levels can separate the elite from the sub-elite athletes in both team and individual sports (Burke, Winslow and Strube, 1980; Fry and Kraemer, 1991; Mahood, Kenefick, Kertzer and Quinn, 2001; Sawyer, Ostarello, Suess and Dempsey, 2002). For example, previous research has shown that both lower and upper body strength and power are contributing factors in American football and rugby league performance (Baker and Nance, 1999; Black and Roundy, 1994; Sawyer *et al.*, 2002). While this appears logical due to the contact nature of the sports, previous studies reveal that these physical characteristics also contribute to the level of athletic performance in sports that are non-contact and predominately aerobic, ranging from soccer (Cometti, Maffiuletti, Pousson, Chatard and Maffulli, 2001) to cross-country skiing (Mahood *et al.*, 2001).

Although these findings highlight how important dynamic power and strength is to sports performance, training methods to optimise these characteristics remain obscure. While numerous studies have looked at variations of strength and power training such as traditional resistance, powerlifting, plyometric and maximal power ballistic exercises (Adams, O'Shea, O'Shea and Climstein, 1992; Comyns, Harrison, Hennessy and Jensen, 2007; Fatouros, Jamurtas, Leontsini, Taxildaris, Aggelousis, Kostopoulos and Buckenmeyer, 2000; Harris, Stone, O'Bryant, Proulx and Johnson, 2000; Lyttle, Wilson and Ostrowski, 1996; Newton and Kraemer, 1994; Wilson, Newton, Murphy and Humphries, 1993), the optimal method of training for athletic preparation is still somewhat unclear.

For example, previous studies have demonstrated that a combined resistance and plyometric training program is more effective for enhancing athletic performance than either method in isolation (Fatouros *et al.*, 2000). However, the optimal order in which these two methods of training should be performed is unknown. In fact, there are a number of potential benefits for performing the plyometric exercises either first, last, in alternation with the resistance training exercises or in a completely separate training session (Baker, 2003; Chu, 1996; Duthie, Young and Aitken, 2002; Fatouros *et al.*, 2000; Masamoto, Larson, Gates and Faigenbaum, 2003).

Contributing to the confusion is the number of different methods of implementing each training regime. For example, previous studies have provided evidence to support the use of a single set of each exercise during training (Graves, Pollock and Foster, 1990; Silvester, Stiggins and McGown, 1982; Stowers, McMillan, Scala, Davis, Wilson and Stone, 1983) whilst other studies have suggested that multiple-set training is superior (Carpinelli and Otto, 1998, Schlumberger, Stec and Schmidtbleicher, 2001; Stone, Plisk, Stone, Schilling, O'Bryant and Pierce, 1998). In addition, the number of training sessions per week, daily undulating versus linear periodisation, light-heavy compared to every session to failure, and the number of sets performed for each exercise are additional concerns which contribute to the complexities of designing an optimal training program.

Despite the variability in training strategies, a common denominator in the majority of previous training studies is the use of the full range of motion (ROM) when performing the exercises. Training throughout the full ROM is believed to both help maintain flexibility and enhance joint stability, and therefore decrease the potential risk of injury (Gross, 2000; Vives, 2000).

While this theory appears plausible, previous studies have shown that bodybuilders who often train with full ROM exercises exhibit dramatically reduced flexibility when compared to non-weight trained individuals, with one causative factor being an increase in muscle bulk (Beedle, Jessee and Stone, 1991). This loss of flexibility may, however, be neutralised to some degree by implementing a stretching protocol into the athlete's training program (Handel, Horstmann, Dickhuth and Gulch, 1997).

Similar to flexibility, joint stability is also optimally trained using other methods. For example, plyometric and proprioceptive exercises are often specifically designed to enhance this characteristic (Kern-Steiner, Washecheck and Kelsey, 1999; Pincivero, Gieck and Saliba, 1993). In fact, traditional full ROM training in isolation has been shown to have a negative effect on performance during cutting tasks while sprinting, suggesting that this method of training may actually have a detrimental effect on joint efficiency (Cochrane, Lloyd, Besier and Ackland, 2003). However, concurrently performing resistance and proprioceptive training has been shown to overcome this negative effect (Cochrane *et al.*, 2003).

The above findings suggest that a long-term athletic training mesocycle should incorporate plyometric, proprioceptive and dynamic movements in supplementation to the resistance training component. By participating in a well-rounded training program, the potential negative effects of traditional resistance training may be overcome. Furthermore, the implementation of these different training methods allows the athlete to specifically target and enhance certain performance attributes. For example, during an explosive power training microcycle, the exercise prescriber may devise a program with the specific goal of enhancing the athlete's explosive power abilities. This training program would include low load/high velocity plyometrics to enhance dynamic power and speed, power training with loads at the athlete's peak power level to enhance ballistic power, and high load resistance training to augment force production. In such a program, the resistance training portion would be specifically implemented to enhance the muscle's ability to produce high force levels. However, it is important to note that a resistance training program utilising the full ROM may not be optimal for enhancing muscle force levels. Previous studies have shown that full ROM exercises consist of a large deceleration phase (Elliott, Wilson and Kerr, 1989; Newton, Kraemer, Hakkinen, Humphries and Murphy, 1996), resulting in a substantial proportion of the movement being performed at force levels far below maximal. From an athlete's point of view, this submaximal performance during the exercise is detrimental in that it occurs towards the terminal phase of the movement, which is often the critical portion for athletic performance. Furthermore, from a performance standpoint, athletes are often required to perform countermovements at various joint angles during sport (Bloomfield, Ackland and Elliott, 1994). Depending on the game play situation, it may be necessary for the athlete to perform dynamic strength movements in a very limited ROM. An example of this could be "palming-off" a tackle in rugby league. The aim of this movement is to prevent the tackle being completed by pushing the opposing player away, similar to an upper body bench pressing movement. An example of palming off during rugby league is provided in Figure 1.1.

A **B** **C**

Figure 1.1. An example of the palming-off movement during rugby league.
A The point of initial contact with the opposition player
B The countermovement position
C The successful pushing away movement.
Images obtained with permission from the study participants game footage.

If the ball carrier was to perform this movement using a full ROM bench press action, with the countermovement occurring at the chest, the defender would then become close enough to grapple the player. Therefore, in this situation the application of near maximal force to the opponent through only a limited ROM near full elbow extension is essential to successfully avoid being tackled. If this movement were to be replicated during the bench press exercise, the actual ROM would likely be only one half of the full ROM from the terminal portion of the movement (i.e. full elbow extension with the shoulder in horizontal flexion). Therefore, the true movement specificity of full ROM training to this action is limited. In an effort to overcome this restriction, it has been suggested that resistance training in a partial ROM that replicates the joint angles involved in sports provides enhanced benefits for improving performance (Bloomfield *et al.*, 1994; Frykman, Morrissey, Harman and Han, 1995; Young, Benton, Duthie and Pryor, 2001; Zatsiorsky, 1995), because full ROM training does not provide an optimal stimulus for performance gains in the specific ROM where the sporting movement often occurs.

Therefore, an athlete participating in a sport that requires maximal intensity countermovement performance at various phases of the ROM may benefit from a resistance training program that replicates these movements. Performing variable ROM (VROM) training, which consists of the countermovement performed during each set taking place at a different joint angle, may help to increase the sports specificity of resistance training. For example, if the athlete was to perform four sets of bench press, the countermovement for each individual set may be performed at full, three quarter (¾), one half (½) and one quarter (¼) ROM of the exercise (see Figure 1.2.).

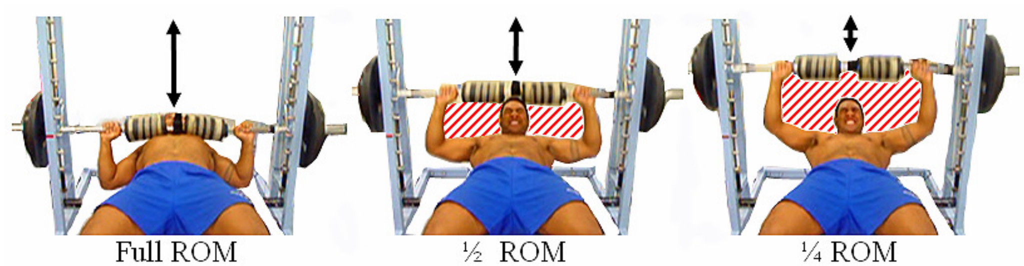

Figure 1.2. Countermovement positions during variable ROM resistance training.
Area in ROM not trained during particular set of variable ROM training.
Area in ROM trained during particular set of variable ROM training.

Consistent with full ROM training, the full ROM set would require the barbell to be lowered to the chest before being lifted to full elbow extension. In contrast, for the ¾ ROM set the barbell would only be lowered ¾ of the distance from full elbow extension to the chest, resulting in a countermovement performed approximately 10-15cm off the chest. The ½ ROM set would be lowered only ½ the distance between the chest and full elbow extension, and the ¼ ROM set is lowered only ¼ of the distance to the chest.

This method of training may provide greater sports-specific benefits, as the body is required to adapt to performing near maximal-intensity countermovements at different joint angles. This variation in the movement scheme utilised during resistance training may have a dramatic effect on the adaptations that occur. It would appear plausible that the neuromuscular system would adapt in a way that optimised force production throughout the entire ROM, potentially via adaptations in neuromuscular activation patterns and/or changes in sarcomere length within the muscle fascicles.

Another potential benefit of VROM training is that the loads used during each set must be modified so that each set is performed at near maximal intensity. This is due to changes in mechanical and neural factors resulting in response to the different countermovement position during each set, such as the moment arm, muscle fascicle and sarcomere length. Subsequently, this method of training requires a different load to be incorporated for each ROM trained, to allow for a similar number of repetitions to be performed maximally during each set. This may permit loads to be incorporated into the training program that far exceed the athlete's full ROM one-repetition maximum (1RM), potentially increasing the eccentric overload placed on the musculature. In well-trained athletes, this may reduce the risk of injury incurred during sports by enhancing their ability to control eccentric loading. Previous research shows that these high levels of eccentric force, when combined with uncontrolled situations, often lead to soft tissue injury (Faulkner, Brooks and Opiteck, 1993; Proske and Morgan, 2001). By preparing the athletes in a controlled manner to face these external forces during competition, we are potentially enhancing their ability to cope with these forces and subsequently minimise their risk of injury. This high level of eccentric force, in addition to the varied movement schemes and the additional loading during the partial ROM sets, may also result in beneficial changes to muscle architectural properties, such as pennation angle and fascicle length. These two properties have been shown to adapt to specific training stimulus (Blazevich, Gill, Bronks and Newton, 2003; Blazevich and Giorgi, 2001), and therefore may respond to a VROM training program by becoming optimised for performance throughout the entire ROM.

Despite the potential for VROM training to provide numerous benefits for athletes, few previous studies have examined the effects of partial or VROM training in either the upper or lower body (Graves, Pollock, Jones, Colvin and Leggett, 1989; Graves, Pollock, Leggett, Carpenter, Fix and Fulton, 1992; Massey, Vincent, Maneval and Johnson, 2005). The majority of these studies have assessed performing the partial repetition training in only one restricted ROM, and have compared this to full ROM training. These studies have often found the strength outcomes to be comparable between the two training groups. However, the partial ROM training group often displays greater strength gains in the trained ROM (Graves *et al.*, 1989; Graves *et al.*, 1992). For example, in the study performed by Graves *et al.*, (1989), the group that trained in the strongest ROM recorded an increase in their strength levels of more than

1.5 times the performance gain noted in the group that trained throughout the entire ROM.

While this previous research shows that there is potential for partial ROM training to improve performance, there are no previous studies which have examined the effect of performing near maximal training with countermovements performed at different joint angles as proposed in the VROM training method. Due to the athletic and normal daily functioning specificity of this method of resistance training, it is therefore important to examine its effect on functional performance.

1.2 Statement of the Problem

While there is no doubt that traditional, full ROM resistance training is an effective method of increasing strength and power, it may not provide optimal stimulus and physical preparation for athletes in sports where countermovements and high force output are needed during different phases of the ROM. Therefore, the primary goal of the current study was to compare the effects of a VROM and full ROM bench press training intervention on professional athletes participating in a sport which demands the performance of near maximal intensity countermovements throughout the ROM.

1.3 Global Hypothesis

The global hypothesis of this thesis is that VROM training will result in significantly greater strength and power performance throughout the entire ROM, especially as the ROM diminishes towards full extension, due to the increased efficiency resulting from training each phase of the movement at near maximal levels.

1.4 Experimental Questions

To experimentally examine this hypothesis, two factors must be assessed to determine the potential benefits of VROM training. These are, in order:

1. It must first be determined if the exercises performed during a VROM training session provide potential intra-session advantages.
2. If VROM resistance training is shown to provide intra-session benefits, it must be determined if this method of training provides longitudinal performance gains when compared to a traditional full ROM resistance training program. If there are differences in performance, it must also be determined what the actual mechanisms behind these adaptations are.

1.5 Significance of this Research

The results of this study may have a major impact on methods of training for enhancing athletic performance. If the results of the present study reveal that VROM training has beneficial effects on performance, it may become a staple in high level training programs. In addition, the results of this study may also be beneficial in rehabilitation and training of other members of the community. For example, the ability to control eccentric loading in older populations at risk of falling is critical. In this population eccentric instability, which may occur when attempting to recover after a trip when walking down stairs, could result in a fall and serious injury. Therefore, a training program that enhances this ability may reduce the potential for injury when encountered with such a potentially dangerous situation.

1.6 Global Limitations and Delimitations

1. The exercise interventions and testing protocols included in this study were limited to those involved in the upper body pressing movement.
2. The subjects involved in this series of experiments are rugby league players, a subset of both the general and athletic population.
3. The testing protocols and interventions were performed during the subject's pre-season training, and therefore external training loads could not be adequately standardised without sacrificing the subject's athletic preparation.

Chapter 2

REVIEW OF LITERATURE

This literature review will assess the potential limitations of traditional, full ROM resistance training for athletic preparation, and explore the potential for variable ROM (VROM) training to overcome these constraints. Literature related to the following sections was reviewed and subsequently presented in this chapter:

1. Principles of resistance training
2. Limitations of full ROM resistance training in regards to the principles of resistance training, including the potential for VROM resistance training to overcome these limitations
3. Research related to VROM training and the potential mechanisms for enhanced performance gains.

2.1 PRINCIPLES OF RESISTANCE TRAINING

This section provides a brief overview of the principles of resistance training that may be limited by full ROM resistance training. The primary aim of this section is to define and briefly explore each principle, with a succinct review of important research examining specificity of training, both in terms of movement and velocity specificity, progressive overloading and variation in a training program.

2.1.1 Specificity of Training

Unless the training program being undertaken by athlete's is specific to their sport, it will be of limited benefit to their athletic preparation (Wilson, Murphy and

Walshe, 1996). Therefore, to provide optimal benefits the resistance training exercises they perform must be specific to the sporting movement they wish to enhance. Previous research has demonstrated that even if a training program is stimulating the correct muscle groups, it may not necessarily lead to improved performance. This may be attributed to mechanical reasons including preferential recruitment of the motor units in the prime leverage positions for the intended movement (Ter Haar Romeny, Denier van der Gon and Gielen, 1982; Ter Haar Romeny, Denier van der Gon and Gielen, 1984). For example, a study performed by Wilson, Murphy and Walshe (1996) examined the effects of an eight-week squat and bench press training program on a wide variety of upper and lower body movements in 27 trained males. These tests consisted of 30% of 1RM bench throws, vertical jump, 1RM squat and bench press, dynamic push-up force, 40 m sprint, six second cycle and isokinetic tests of the upper and lower body.

The results of this study suggested that posture during training is important in transferring the benefits of the resistance exercise to athletic performance, both for the upper and lower body musculature. One of the more interesting findings of the study was that even though 1RM bench press (12.4%), isokinetic bench press torque (12.8%) and bench throw power (8.4%) all increased significantly, there was only a marginal improvement in force production during the push-up test (0.7%). This finding occurred despite the fact that the push-up movement recruits similar muscle groups to the bench press exercise (Wilson, Murphy and Walshe, 1996). The investigators theorised that the benefits of training were posture-specific, and are related to the neural input received by the involved muscle groups. This suggests that if the resistance training performed does not closely replicate the athletic movement, there may be only a limited crossover in performance gains from the weights room to the sporting field.

While the findings of Wilson, Murphy and Walshe (1996) suggest that resistance training exercises must replicate the movements utilised during a specific sport, there are also a number of previous studies suggesting that resistance exercises may be more beneficial if they are also velocity-specific. Proponents of velocity-specific training suggest that to enhance ballistic performance, the training velocities must replicate the speeds used during the sport (Cronin, McNair and Marshall, 2002). While not incorporating sporting movements, a number of previous studies have found a velocity-specific training response to isokinetic exercise (Caiozzo, Perrine and Edgerton, 1981; Coyle, Feiring, Rotkis, Cote, Roby and Lee, 1981; Kanehisa and Miyashita, 1983). However, in terms of traditional resistance exercises, the velocity-specific training results have varied considerably (Cronin *et al.*, 2002; Cronin, McNair and Marshall, 2003; Wenzel and Perfetto, 1992). A discussion of these variable results for velocity-specific training will be provided later in this literature review.

2.1.2 Progressive Overloading

Regardless of the specificity of the exercises implemented, if the training program does not progressively overload the athlete the performance gains will diminish over time. This is because as an athlete who undertakes resistance training becomes more advanced, the potential for improving performance is gradually reduced (Kraemer, Adams, Cafarelli, Dudley, Dooly, Feigenbaum, Fleck, Franklin, Fryk, Hoffman, Newton, Potteiger, Stone, Ratamess, and Triplett-McBride, 2002). In fact, the vast majority of previously cited resistance training studies have demonstrated that nearly all methods of resistance training will produce beneficial adaptations in untrained subjects regardless of the method of overloading incorporated (Fleck, 1999; Hakkinen, 1985). However, as the athlete's resistance training experience increases, the importance of progressively overloading their training program is augmented. This progressive overload is defined as "the gradual increases of stress placed upon the body during exercise training" (Kraemer *et al.*, 2002).

Progressive overloading is essential to ensure that the athlete does not reach a plateau in their resistance training performance, a point at which improvements diminish. These performance plateaus occur because the human body is extremely adaptable, and will quickly create a tolerance to the current level of stimulus it receives from a training program (Kraemer *et al.*, 2002). Therefore, unless a greater magnitude of stress is applied to the body it will cease to adapt. To counter this problem, previous research has demonstrated a number of ways in which overloading may be carried out. These include increasing the load or resistance, performing more repetitions with a given load, escalating the volume of work performed, modifying the tempo of the exercise, altering the rest periods and augmenting contraction specific overload, which consists of emphasising one phase of the movement (Kraemer *et al.*, 2002).

While the aforementioned list provides a number of potential methods of progressive overloading, many of these factors are intrinsically linked. For example, if any one of the variables such as the load lifted, the number of sets or the number of repetitions performed are altered, then there is a subsequent change in the volume of work performed. Although this multi-factorial nature of progressive overloading would appear to provide plenty of scope for increases in volume, as an athlete's resistance training experience increases it can become increasingly difficult to continuously overload their training program.

2.1.3 Variation

One method of overcoming performance plateaus is to vary the types of exercises included in the training schedule. The necessity of variation in an athlete's training program is related to the concepts of specificity and progressive overload. In terms of specificity, if the resistance training program continually incorporates the same exercises, the muscular system will adapt by creating a neural drive that is only efficient for those movements (Ter Haar Romeny *et al.*, 1982; Ter Haar Romeny *et al.*, 1984). However, for athlete's participating in team sports or events where a wide variety of movements are necessary, this may limit their performance. Furthermore, limited variation in a training program may also lead to muscular imbalances, which are a major risk factor for injury (Coombs and Garbutt, 2002). With respect to progressive overloading, a limited variety of exercises may also lead to both physical and mental performance plateaus (Kraemer *et al.*, 2002).

2.1.4 Summary of the Principles of Resistance Training

To optimise performance gains, a resistance training program must be movement specific, provide progressive overloading and contain sufficient variation (Kraemer *et al.*, 2002). However, the sole usage of full ROM resistance training places certain limitations on the ability of the exercise programmer to continually adapt a training program to ensure long-term performance progression. The following sections assess the limitations of full ROM training for enhancing performance in regards to each of the above principles of training, and the potential for VROM training to overcome these limitations.

2.2 LIMITED MOVEMENT SPECIFICITY OF FULL ROM TRAINING

As previously discussed in the review of movement specificity (Section 2.1.1), it is essential that the exercises in an athlete's resistance training program replicate the movements performed in their sport. However, the true movement specificity of full ROM training to sporting performance often appears limited. To provide a sporting example, during a serve in tennis the athlete might lower themselves into a deep squat position before performing a countermovement and exploding upwards to hit the ball. In contrast, when the athlete is pursuing the tennis ball around the court, which requires sprinting and cutting movements, their knee flexion angles during the countermovements may vary between near complete knee extension and deep knee flexion. Consequently, while the full ROM squats are likely to assist in the jumping countermovement, assuming it takes place at a similar joint angle, the full ROM squat is unlikely to provide optimal neuromuscular adaptations to enhance countermovement performance for the sprinting and cutting tasks.

To overcome this limitation, it has been suggested that resistance training in a partial ROM that replicates the joint angles involved in sports will be more beneficial for enhancing performance (Bloomfield *et al.*, 1994; Zatsiorsky, 1995). This has been advocated because full ROM training may not provide an optimal stimulus for performance gains in the specific ROM where the sporting movement often occurs. This is due to a number of factors that will be discussed in the following sections. These aspects are:

1. Terminal deceleration and the limited ROM in which peak force is produced
2. Non-specific countermovements
3. Limited eccentric overloading
4. The force/muscle length relationship
5. Detrimental effects on muscle architecture

2.2.1 Terminal Deceleration

Although full ROM resistance training requires the movement of a load throughout the entire ROM of an exercise, the intensity of the movement varies dramatically. A study by Lander, Bates, Sawhill and Hamill (1985) examined force curves during both traditional and isokinetic bench press movements (see Figure 2.1.).

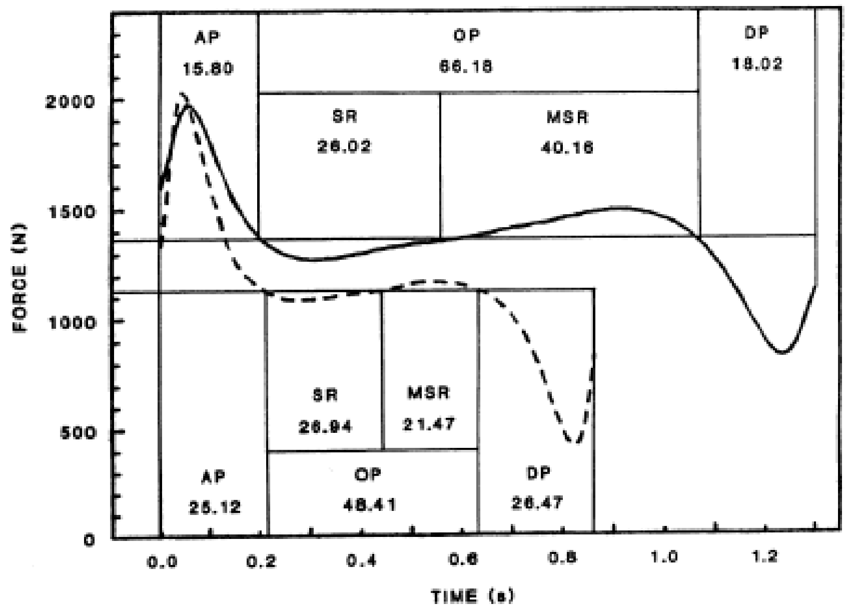

Figure 2.1. **Force curves during the bench press exercise.**
This figure represents the force curves occurring during heavy (90% of 1RM — solid line) and moderate (75% of 1RM --- dashed line) load bench press.

AP Acceleration phase of the lift
OP Oscillation phase
SR Sticking region
MSR Maximum strength region
DP Deceleration Phase

The values given for each region represents the percentage of the full ROM that each region occupied (from Lander *et al.*, (1985), p.346).

Force output for 75% and 90% of 1RM free weight bench press was found to peak rapidly at 1.8% and 1.7% of the ROM, respectively, which corresponded to a bar position of 0.82 and 0.86 cm from the chest. By the time the bar had moved 25% of the full ROM, the force value was almost half that of the peak force in the 75% of 1RM test. This moderate force level remained relatively stable before a further dramatic drop-off in the final 26.5% of the movement. This final drop-off phase was termed the deceleration phase of the lift as the bar reaches terminal extension. The 90% of 1RM test also produced a similar force curve, however, the force output did not drop as severely as that of the 75% of 1RM test.

The dramatic reduction in force after the initial peak, along with the deceleration phase, potentially limits the specificity of traditional full ROM resistance training exercises to sporting performance. Similar deceleration phases of between 24% and 40% of the concentric bench press ROM have also been reported in previous literature (Elliott *et al.*, 1989; Newton *et al.*, 1996). The dilemma is that this deceleration phase of the lift occurs in the ROM in which a large number of sporting movements require maximal force output. This suggests that full ROM resistance training produces peak force at the opposite end of the ROM to what the majority of movements in sport require. Furthermore, velocity-specific training using low load resistance training exercises appears to result in an even greater ROM spent in the deceleration phase (Cronin *et al.*, 2002). A large deceleration phase during terminal extension may hinder the application of velocity specific resistance training exercises to any sport where ballistic movements are necessary.

In contrast, by performing VROM resistance training the athlete would be required to exert dynamic peak force at different stages of the ROM with a greater load. This increased load may result in a smaller deceleration phase, as the higher load, in combination with the limited ROM, may result in less time needed to decelerate from maximal to zero velocity. Therefore, this would suggest a more plateaued peak in the force-curve characteristics. However, whether the performance of VROM training has an effect on the terminal deceleration phase of the concentric movement remains unknown.

Three methods of resistance training that have specifically attempted to overcome the limitations imposed by terminal deceleration are functional isometric

(Giorgi, Wilson, Weatherby and Murphy, 1998), variable resistance (Manning, Graves, Carpenter, Leggett and Pollock, 1990) and ballistic training (Wilson *et al.*, 1993). Functional isometric training is almost identical to full ROM resistance training. However, during the concentric phase of the lift a maximal voluntary isometric contraction is included at either the sticking point or in the region of maximal strength (Giorgi *et al.*, 1998). For example, during the bench press exercise, stoppers on a Smith machine may be set at a point approximately 25% of the ROM from the chest. The athlete would lower the barbell to their chest, perform the countermovement and execute the concentric contraction. In contrast to a traditional bench press, when the barbell reaches the stoppers the athlete would push as hard as possible against the immoveable resistance. This isometric contraction results in peak force levels in a region of the lift where force production would typically taper off.

While previous research suggests that functional isometric training may provide some potential benefits in comparison with traditional full ROM resistance training (Giorgi *et al.*, 1998), it does have limitations in regards to movement specificity. Firstly, by including an isometric contraction into the bench press exercise, the ROM becomes limited in an opposing way to VROM training. Instead of limiting the ROM from full extension, which is often the case during sporting movements, the ROM is restricted in a way that prevents full extension being reached. Therefore, even though higher force levels may be achieved in phases of the ROM that are more sport specific than during full ROM bench press, the movement specificity of the exercise is diminished. Secondly, the inclusion of an isometric contraction into the exercise, while producing high force levels, may only have a limited transference to dynamic performance. Previous studies have found poor correlations between isometric strength and dynamic athletic performance (Murphy and Wilson, 1996), and even though there would appear to be potential benefits of performing functional isometric training, the results of the previous training study were inconclusive (Giorgi *et al.*, 1998).

The second method of resistance training that specifically attempts to overcome the limitations imposed by terminal deceleration is variable resistance training. This method of training attempts to accommodate the muscle's changing force output throughout the ROM by varying the external resistance (Manning *et al.*, 1990). This is commonly achieved by using equipment, such as the products by Nautilus™, which have specially designed cams that increase the resistance during the muscle's strongest phase of the ROM. Therefore, because the resistance is increased throughout the ROM, the terminal deceleration phase of the movement becomes less pronounced. While this method of training does appear to provide some benefits when compared with traditional constant resistance full ROM training, previous research examining its superiority has provided disparate results (Anderson and Kearney, 1982; Manning *et al.*, 1990). For example, a six month training intervention consisting of 28 subjects performing either variable resistance or traditional weight training observed no significant differences in any performance measures between groups (Hunter, Wetzstein, McLafferty, Zuckerman, Landers and Bamman, 2001).

The third method of training that attempts to overcome terminal deceleration is ballistic training. This form of training endeavours to remove the deceleration phase altogether, by having the athlete propel the weight at the end of the movement. Although previous studies have shown mixed results in regards to the effect of ballistic training on the velocity profile of the movement (Cronin *et al.*, 2003; Newton, Murphy, Humphries, Kraemer and Hakkinen, 1997), this method of training is known to be highly effective for enhancing functional performance (Lyttle *et al.*, 1996), and the inherent nature of the exercise suggests that it must have an effect on terminal deceleration.

Functional isometric, variable resistance and ballistic training may provide benefits with respect to terminal deceleration. However, these methods of training fail to overcome one of the major limitations of full ROM resistance training, the non-specific position of the countermovement in regards to sporting movements.

2.2.2 Non-specific Countermovements

The second limitation of full ROM resistance training in regards to enhancing athletic performance is the single countermovement position. A countermovement is the eccentric to concentric changeover that occurs at the bottom of a movement, allowing for a reversal in the direction of the displacement vector. An example of this is in the contraction of the pectoralis major during a ballistic bench throw. When the athlete lowers the barbell towards their chest, which results in active lengthening of the muscle, this is the eccentric phase of the movement. To perform the throw, the athlete must then counter this movement by performing a concentric contraction. This results in an eccentric - concentric chain of movement termed the stretch-shortening cycle (Bobbert, Gerritsen, Litjens, and Van Soest, 1996; Harman, Rosenstein, Frykman, and Rosenstein, 1990). A number of previous studies have shown that performing a countermovement prior to a concentric contraction dramatically improves performance (Bobbert *et al.*, 1996; Harman *et al.*, 1990). The increase in concentric performance during the stretch shortening cycle is predominately dependent on the utilization of elastic energy stored during the eccentric phase of the countermovement (Bobbert *et al.*, 1996; Harman *et al.*, 1990).

Despite the lengthening of the musculotendinous unit during the eccentric phase of the countermovement, previous research suggests that in situations of rapid countermovement the actual contractile components of this complex do not exhibit a major change in length (Reeves and Narici, 2003). These components, which are made up of the muscle fascicles, have been shown to contract quasi-isometrically during intense eccentric contractions (Reeves and Narici, 2003). This suggests that the non-contractile elastic component of the musculotendinous unit, comprising the tendons and aponeuroses, undergoes a considerable elongation. This stretching of the tendon results in storage of elastic energy to be released during the concentric phase of the movement. By releasing the stored energy, in addition to the force produced by the contractile components of the musculotendinous system, a considerable improvement in performance is obtained (Bobbert *et al.*, 1996; Harman *et al.*, 1990). In fact, one previous study suggests that the ability to perform the countermovement efficiently is an even more important factor than concentric strength in dynamic movements such as sprinting (Young, Wilson and Byrne, 1999).

While providing obvious performance benefits, this previously mentioned quasi-isometric nature of the eccentric contraction may place a high degree of stress and strain on the muscle contractile units. When the muscle's sarcomeres are lengthened in an eccentric contraction, it is unlikely that the actin-myosin crossbridging is reliant on ATP dependent attachment (Enoka, 1996). This is because the muscle fibre does not have to overcome an external force, but resist it. Therefore, the sarcomere does not have to expend energy producing a shortening contraction against an external load. In contrast, it may have to mechanically control its lengthening by preventing the actin-myosin coupling from separating. Evidence of this has been shown in studies that have revealed little difference in muscle activation during eccentric contractions performed at different velocities (Colduck and Abernethy, 1997; Cramer, Housh, Evetovich, Johnson, Ebersole, Perry, and Bull, 2002; Smith, Housh, Johnson, Evetovich, Ebersole and Perry, 1998; Westing, Cresswell and Thorstensson, 1991), and minimal metabolic cost during this form of contraction (Enoka, 1996; Van Ingen Schenau, 1984). Despite changes in the force velocity relationship, these previous studies have shown that there is only minor muscle activation and energy expenditure during eccentric contractions, and that the magnitude of difference between velocities is negligible (Kawakami, Muraoka, Ito, Kanehisa and Fukunaga, 2002). Although minimising metabolic cost, this mechanical control phenomenon may play a large role in the occurrence of soft tissue injuries during eccentric contractions (Enoka, 1996). The mechanical disruption of the actin-myosin crossbridge could play a part in the numerous abnormalities that occur after an intense eccentric contraction, such as disruption of the sarcomeres, fragmentation of the sarcoplasmic reticulum, cytoskeletal damage and swollen mitochondria (Enoka, 1996; Friden and Lieber, 1992; Stauber, 1989).

With respect to functional performance, a greater ability to exert this quasi-isometric strength during an eccentric contraction may lead to a more efficient and less damaging countermovement. Theoretically, it can be hypothesised that the contractile components would then be able to maintain the actin-myosin crossbridging at higher strain levels, and therefore, more of the musculotendinous lengthening would be undertaken by the tendon. This could result in a more efficient countermovement that may provide a shorter amortization, or stationary, phase and greater contribution of elastic energy to the concentric phase of the movement.

Although the phases of the countermovement prior to the concentric contraction appear to be quasi-isometric, emphasising the static section of the movement during training does not enhance subsequent countermovement performance. A study by Toumi, Thiery, Maitre, Martin, Vanneuville and Poumarat, (2001) examined the effect of altering the amortization phase of a lower body countermovement exercise on performance. In this study, 42 previously sedentary young males were split into four groups, with each group completing an eight week training study. All participants performed six sets of 10 repetitions of Smith machine squats four times a week as the training exercise. However, each group performed the squat exercise in a different fashion. The first group performed their squats with a two second un-weighted pause at the bottom of the movement. The second group performed the squat with a two second isometric hold at the bottom of the movement. The third group performed a dynamic countermovement with no pause. Finally, the fourth group was a control group and performed no exercise.

The results of the above study showed that all three training groups achieved a significant increase in both static-start jump height (Group 1: 14.3%, Group 2: 15.7%, Group 3: 17.8%) and isometric strength (Group 1: 11.8%, Group 2: 14.8%, Group 3: 9.3%) after the training intervention. However, only the dynamic countermovement group achieved a significant increase in countermovement jump height (Group 1:

3.2%, Group 2: 3.2%, Group 3: 20.0%) post-intervention. The researchers hypothesized that training with an extended amortization phase hindered the neurological adaptations that allowed for enhanced stretch-shortening cycle performance.

These findings suggest that it is important to perform a dynamic countermovement during training to enhance stretch-shortening cycle performance. Theoretically, every countermovement performed during resistance training is producing a stimulus made up of all three different types of contraction, with the almost instantaneous isometric contraction playing a large role in the efficiency of the movement. It is therefore plausible that this stimulus would result in adaptations to the common drive of the musculature in an effort to enhance countermovement performance. While there is a dynamic countermovement performed during full ROM resistance training exercises, this may not be optimal for enhancing sporting performance due to the stretch-shortening cycle movement occurring in the same position during each repetition. Therefore, continuously performing the countermovement when the agonist muscle is at its longest position in the ROM of the exercise does not replicate the positions where countermovements are performed during sports.

In contrast, this non-specific countermovement position imposed during full ROM training would be eliminated by VROM training. The combination of partial ROM training sets performed at various joint angles may create a more effective neural program for countermovement performance throughout the entire ROM. However, while previous research has shown that gains in isometric strength after performing isometric training are limited to similar joint angles as those trained (Gardner, 1963; Lindh, 1979), whether the benefits of resistance training with dynamic countermovements are limited to the ROM where the amortization phase occurs is currently unknown.

Despite this uncertainty, a more recent study performed by Barak, Ayalon and Dvir (2004) may give an insight into the effects of partial ROM training on force production. In this study 55 women (age: 23.5 $\pm$ 1.4 yr, height: 165.2 $\pm$ 5.9 cm, mass: 56.4 $\pm$ 6.7 kg) were randomly assigned into four groups. Each group performed a six week training intervention consisting of four sets of 10 repetitions of isokinetic training. Group one trained using concentric knee extension only at $30^{o}{\cdot}s^{-1}$. Group two performed concentric knee extensions at $90^{o}{\cdot}s^{-1}$. Group three completed eccentric knee flexion at $30^{o}{\cdot}s^{-1}$ while group four performed eccentric knee flexion at $90^{o}{\cdot}s^{-1}$. All groups performed their exercises throughout a partial ROM between 30^{o} and 60^{o} of full knee extension. The important findings were that both isometric rate of force development (RFD) and isokinetic strength appeared to result in non-ROM specific gains. However, these gains were only evident at longer muscle lengths than that which was trained. The RFD for the two concentric training groups increased significantly within the training ROM (Group one p<0.001, 69.0% increase, Group three p=0.005, 70.7% increase), with a non-significant trend suggesting an increase at a longer muscle length (Group one p=0.145, 23.0% increase, Group three p=0.069, 33.6% increase). However, RFD at a shorter muscle length than that trained resulted in only very minor changes (Group one p=0.746, 4.2% increase, Group three p=0.863, 2.2% decrease). Similar findings were observed for the isokinetic tests, with an analysis of these results revealing that while the gains in work performed were of a similar magnitude in both the trained ROM and at longer muscle lengths, they were significantly larger than the improvements at shorter muscle lengths.

The aforementioned results are relevant to this review for two important reasons. Firstly, it shows that isometric RFD performance enhancement is ROM specific. Although this does not specifically imply that countermovement performance enhancement is ROM specific, the similarities between the two contraction modes suggest that this may be the case. Secondly, the above results reveal that partial ROM training in the midrange of the movement increased performance both in the trained region and at longer muscle lengths, but not at shorter muscle lengths nearing terminal extension. The researchers suggested that this may be attributed to the effect of increased RFD on the force curve. This midrange training increased RFD, thus skewing the force/ROM curve to the left.

While this leftward skewing of the force/ROM curve may improve weightlifting potential, it would not provide optimal adaptations for athletes who are required to perform countermovements in different phases of the ROM. Therefore, it would appear that ROM specific countermovement training may be necessary to provide optimal performance gains.

2.2.3 Limited Eccentric Overloading

Another potential method of enhancing sports specific countermovement performance may be to emphasise eccentric overloading. As discussed in the previous section, the efficiency of the eccentric contraction during a countermovement is a major component of elastic energy contribution to the subsequent concentric contraction. While full ROM resistance training does possess an eccentric component, the actual stimulus it presents when compared to the concentric phase is relatively small. This is because the force that can be exerted during eccentric contractions is much larger than the force employed during concentric contractions. For example, the ratio of eccentric to concentric strength for the elbow flexors is believed to be approximately 1.3:1 (Griffin, 1987). Therefore, even if the weight being lifted concentrically for a bicep curl is the maximum that can be lifted for one repetition, it only makes up roughly 77% of the athlete's eccentric 1RM. When you consider that the majority of weight training programs perform numerous repetitions with a percentage of the athlete's concentric 1RM, the percentage of eccentric 1RM is often very low.

One method of increasing the eccentric overload occurring during the eccentric portion of the lift is to 'drop' the weight quickly, without emphasis on the contraction of the muscle. This would result in reduced stress placed on the muscles at shorter lengths, as no eccentric control is required while dropping the weight. In contrast, the higher velocity of the bar during the drop would require greater eccentric braking of the descent. While this would appear to increase eccentric overloading, it is often avoided because of the potential for injury, especially in exercises such as bench press and squats. Another proposed method of overcoming the injury risk factor and increasing the eccentric intensity is to assign a tempo that the repetitions are to be performed to (Bompa and Carrera, 2005). For example, during the eccentric phase of the lift the athlete may be required to lower the weight so that it takes several seconds for the mass to move from the end of the concentric phase to the countermovement stage of the lift. Although this does help to increase the stability of the eccentric phase, it reduces the amount of eccentric force produced by the involved muscle groups. This is because the force-velocity relationship for eccentric contractions suggests that the lower the velocity of the eccentric contraction, the smaller the force produced (Kues and Mayhew, 1996). Therefore, purposefully reducing the velocity of the movement as a method of increasing the intensity actually results in lower force production at the countermovement position, and a subsequently reduced force inspired stimulus for eccentric strength enhancement.

Although the potential for eccentric overloading during full ROM resistance training is limited, it appears that training programs involving ballistic countermovements preceded by dynamic eccentric contractions would provide greater gains in eccentric strength compared to slow velocity eccentric contractions. This concept was highlighted in the study performed by Wilson, Murphy and Giorgi (1996). The investigators compared 41 subjects with a prior resistance training background who participated in either a control, heavy weight training or plyometric training intervention for eight weeks. The results revealed that the dynamic, eccentric contractions performed during plyometric training had a beneficial effect primarily on eccentric strength, whereas the heavy weight training resulted in predominantly increased concentric strength. These results suggest that the dynamic eccentric braking that takes place prior to the countermovement during plyometric exercise increases eccentric strength levels. In fact, previous research shows that the faster the eccentric contraction during plyometrics, the greater the magnitude of performance gains (Toumi, Best, Martin, F'Guyer and Poumarat, 2004). In contrast, the slower, more controlled eccentric braking occurring during traditional full ROM weight training has a limited effect on eccentric strength levels.

The results of the training study by Wilson, Murphy and Giorgi (1996) appear to be substantiated by the current literature on muscle activation during eccentric contractions. As previously mentioned (refer to Section 2.3.2.), a number of studies assessing EMG of muscles during eccentric contractions have shown that motor unit firing rates and torque production vary little when the speed of the eccentric contraction is altered (Colduck and Abernethy, 1997; Cramer *et al.*, 2002; Smith *et al.*, 1998; Westing *et al.*, 1991). However, during isotonic stretch-shortening cycle movements, an increase in the velocity of movement requires a substantially greater eccentric braking force to produce the countermovement. Therefore, when a plyometric exercise consisting of a rapid eccentric braking contraction is compared with a slow tempo, high load weight training eccentric contraction, despite the lower external load the plyometric exercise would require greater eccentric force output to efficiently perform the countermovement.

Although the Wilson, Murphy and Giorgi (1996) study revealed that weight training is not as effective as plyometrics for increasing eccentric strength, isokinetic studies have shown the enormous potential of eccentric strength training for improved sporting performance. For example, Friedmann *et al.* (2004) compared a concentric/eccentric training intervention with a concentric/eccentric overload intervention. Eighteen, untrained male subjects of unstated age participated in a four week leg extension training program with loads equivalent to 30% of the subject's 1RM. These subjects were split into two groups, with the control group (CON) using a load of 30% of concentric 1RM for both the concentric and eccentric phases of the lift while the experimental group (EXP) performed the exercise with 30% of concentric 1RM and 30% of eccentric 1RM loading for the respective phases of the movement.

Both groups performed sets of 25 repetitions of the leg extension three times per week, however the CON group performed six sets per session whereas the EXP group performed only three sets. Isokinetic concentric knee flexor and extensor strength, muscle cross-sectional area and muscle biopsies were performed pre and post-training intervention. The findings of this study resulted in the researchers suggesting a dramatic shift towards a more type II dominated gene expression pattern occurred in the muscles of the EXP group, in comparison to only negligible metabolic changes occurring in the muscles of the CON group. This emphasis on the concentric phase of the exercise would lead to preferential activation of the slow twitch muscle fibres according to the motor unit recruitment theory (Fleck and Kraemer, 1997), and hence the muscle's limited adaptations towards a more glycolytic nature.

In contrast, the results of the Friedman *et al.* (2004) study suggest that to enhance the dynamic force required in sports, a training program with eccentric overloading is beneficial due to the preferential activation of the fast twitch motor units. This activation strategy during the overloaded eccentric phase may lead to greater stimulation of the fast twitch muscle fibres, and therefore an enhanced adaptation response in comparison with the traditional concentric biased training regimen. These physiological changes, resulting in response to eccentric overloading, are in opposition to the results of a number of previous studies which have examined the effect of predominantly concentric biased training interventions on muscle adaptation. Many of these prior studies have shown a shift in the muscle's properties towards a less glycolytic nature (Adams, Hather, Baldwin and Dudley, 1993; Andersen and Aagard, 2000; Carroll, Abernethy, Logan, Barber and McEneiry, 1998; Colliander and Tesch, 1990; Hortobagyi, Dempsey and Fraser, 2000; Staron, Karapondo and Kraemer, 1994; Williamson, Gallagher, Carroll, Raue and Trappe, 2001; Willoughby and Rosene, 2001), although a number of studies examining the effect of high intensity resistance training have shown similar findings to the results for the eccentric group in the Friedmann *et al.* (2004) study (Costill, Coyle, Fink, Lesmes and Witzmann, 1979; D'Antona, Lanfranconi, Pellegrino, Brocca, Adami, Rossi, Moro, Miotti, Canepari and Bottinelli, 2006; Sale, MacDougall, Always and Sutton, 1987.

While eccentric overloading appears to enhance dynamic force production through beneficial muscle fibre adaptations, it may have some potentially negative effects on muscle architecture. A number of previous studies have found that performing eccentric specific training causes a rightward shift in the force-length relationship (Byrne, Eston and Edwards, 2001; Child, Saxton and Donnelly, 1998; Clark, Bryant, Culgan and Hartley, 2005; Jones, Allen, Talbot, Morgan and Proske, 1997; Saxton and Donnelly, 1996; Whitehead, Allen, Morgan and Proske, 1998). This shift in the relationship is believed to be due to overstretched sarcomeres in the muscle fascicles, often referred to as the 'popping sarcomere' theory (Morgan and Allen, 1999; Proske and Morgan, 2001). These overstretched, damaged sarcomeres are unlikely to produce active tension, and therefore require the remaining sarcomeres to provide the contractile force. However, because of the increased length of the disabled sarcomeres the actin-myosin overlap for the remaining sarcomeres may be greater than optimal. Therefore, the remaining sarcomeres will be unlikely to reach their optimal level of overlapping, and therefore force production, until the muscle is at a greater length.

While previous reports have suggested that this may reduce the risk of soft tissue injury (Proske and Morgan, 2001), this adaptation does not appear to be efficient for force production during limited ROM movements. The result of this adaptation is that while force production at long muscle lengths will be enhanced, force production at shorter muscle lengths will be reduced. By modifying the position of peak force production to a longer muscle length, potential force production at shorter muscle lengths may be compromised. As previously mentioned, force production at short muscle lengths, towards the terminal extension of the ROM, may be the most important phase for many sporting movements. Therefore, training protocols that incorporate the benefits of eccentric overloading while reducing the effects on the force-length relationship may provide optimal performance gains.

According to Proske and Morgan (2001), this loss of force potential at shorter muscle lengths can be overcome by an increase in the length of the muscle while maintaining or reducing tendon length, with an example provided in Figure 2.2.

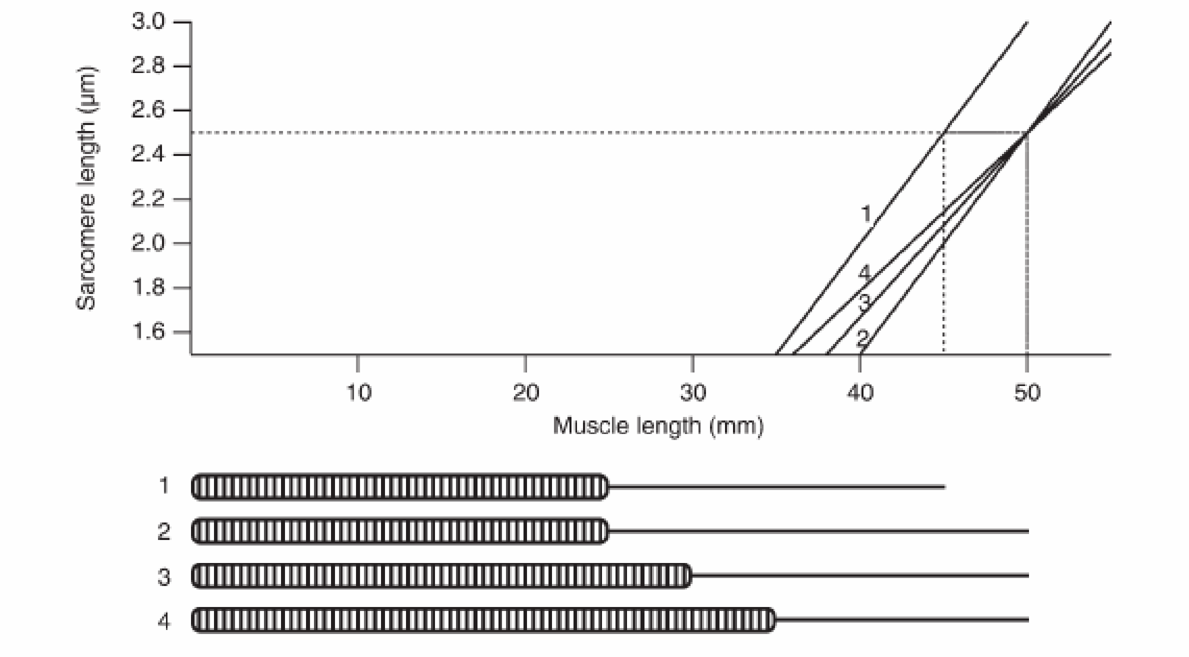

Figure 2.2. The relationship between sarcomere and musculotendinous length.

For this explanation it is assumed that the optimal sarcomere length is 2.5 µm. In this case, for a muscle fibre with 10000 sarcomeres and 20 mm of tendon (represented by fibre 1), tension begins to rise at a muscle length of 35mm and reaches the optimum position at 45 mm. A shift in optimum length for active tension by 5 mm in the direction of longer lengths can be achieved by increasing the length of the tendon to 25mm while maintaining identical muscle length (represented by fibre 2). The problem with this change is that active tension is not produced until the muscle is at a longer length. However, this can be overcome to some extent by maintaining this longer musculotendon length while increasing the muscle to tendon length ratio (represented in fibre 3, and more dramatically in fibre 4). This may occur as a result of an increase in the number of sarcomeres present in the muscle (from Proske and Morgan (2001), p.340).

While the above representation is simplistic, and does not take into account the variation in sarcomere lengths throughout the length of the fascicle or the stiffness properties of the musculotendinous unit, it does provide some insight into how changes in musculotendinous properties may effect force production. If this theory is correct, it may support the use of VROM training in comparison to partial ROM training in only a single, limited range of the movement. Performing partial ROM training in only the strongest ROM requires high force production in only a single countermovement position. This may result in sarcomere length adaptations that would be severely biased towards force production at short muscle lengths. However, the problem with this adaptation is that at long muscle lengths, a greater ratio of the sarcomeres may be required to contract during the descending limb of the length tension relationship. Subsequently, the potential damage associated with trauma to the sarcomeres during eccentric contractions at long muscle lengths would be elevated. This adaptation could then increase the risk of muscle strains and tears.

In contrast, the use of VROM training with countermovements performed throughout the ROM may limit this negative effect. The sarcomeres in the fascicle would be more likely to adapt in a way that optimises force production throughout the ROM, potentially overcoming the force production bias of the partial ROM only resistance training. An example of the potential for fascicles within a muscle group to achieve their optimal length at different overall muscle lengths is provided in Figure 2.3.

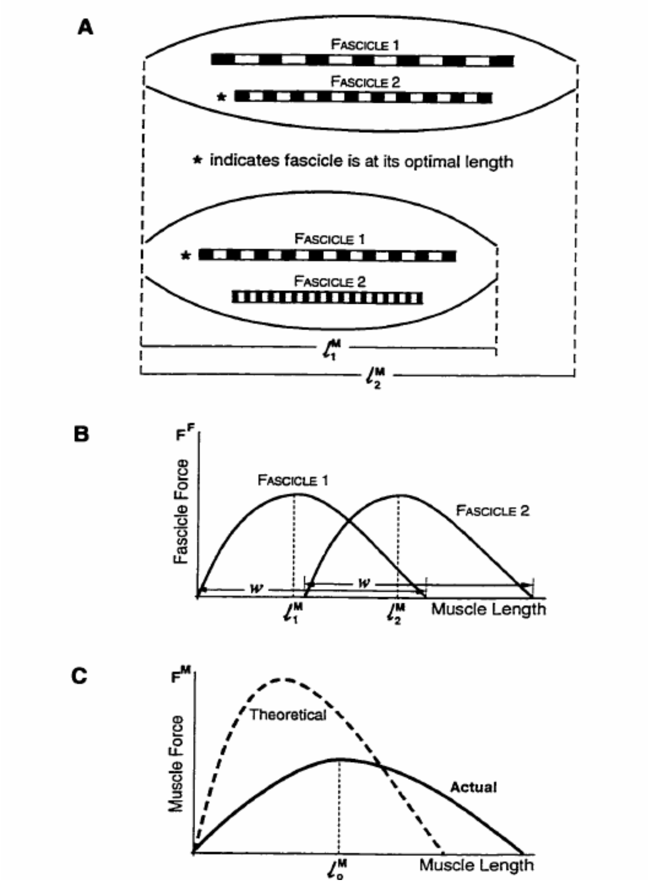

Figure 2.3. The effect of mean sarcomere length on force production. These images provide a comparison of the effects of two muscle fascicles with differing mean sarcomere lengths on force production throughout the ROM.

A This figure displays two muscle fascicles, both within the same muscle group, with heterogenous mean sarcomere lengths and therefore differing optimal lengths in relation to overall muscle length.

B This figure provides the fascicle force – muscle length relationship for the two fascicles, with the peak fascicle force occurring at different muscle lengths due to the optimal length of the sarcomeres.

C This figure outlines the muscle force – muscle length relationship. The dashed line, representing the theoretical entire muscle group force – length relationship, assumes homogeneity of both sarcomere and fascicle positions of optimal length within the ROM. The solid line, representing the actual entire muscle group force – muscle length relationship, is indicative of a muscle group that contains fascicles that produce optimal force at different stages of the ROM. Although peak force is higher in the theoretical muscle group, due to synchronisation of the muscle length at which peak force is produced, the active force range is dramatically reduced (from Pappas (2001), p.107).

Whether these adaptations take place are unknown, however, the potential for partial ROM training to enhance eccentric overload has been previously reported. Mookerjee and Ratamess (1999) assessed joint action durations between partial and full ROM bench press and suggested that partial ROM training may provide superior eccentric overloading. In this study, five strength trained (10.0 $\pm$ 4.2 years experience) males with no prior partial ROM training history completed two testing sessions. In the first session, the subjects were required to perform 1RM and 5RM tests for the full ROM bench press with a three to five minute rest period between tests. A ten minute break was then allowed before the subjects were required to perform their 1RM and 5RM tests for partial ROM bench press strength, with the countermovement performed at an elbow angle of 90^{o}. Identical tests were performed during the second session, however the order of the tests was randomized. Strength levels and elbow joint action durations using electrogoniometry were recorded during all trials.

The researchers reported a significant ($p<0.05$) increase in partial ROM bench press strength under both loading conditions (5.8% and 4.1% for the 1RM and 5RM tests, respectively), and no difference in full ROM strength (mean data not supplied) between the two testing sessions. Although a number of potential factors were cited for this difference, the most plausible reason may be the level of fatigue incurred during the testing in the first session. The fact that all full ROM testing sets were performed prior to the partial ROM trials on the first day while the order was randomized during the second session suggests that the testing order would have greatly affected the results. Although the order of testing was somewhat flawed, an interesting finding was reported in terms of the elbow joint angle durations, which provided a measure of the time taken for each phase of the movement. While no exact bar displacements were reported in this study, it can be assumed that there was significantly less vertical displacement during the partial ROM bench press in comparison with the full ROM repetitions. However, the investigators stated that the elbow joint action durations for the partial ROM bench press were significantly shorter during the extension phase (partial ROM: 2490.4 $\pm$ 1564.1 ms vs. full ROM: 4376.8 $\pm$ 981.3 ms) but only negligibly different in the flexion stage of the movement (partial ROM: 1578.2 $\pm$ 383.3 ms vs. full ROM = 1724.1 $\pm$ 551.6 ms). The aforementioned results suggest that while the concentric phase of the movement was performed at a similar velocity during partial ROM repetitions, there was little difference in the eccentric contraction despite the decreased bar displacement.

Although the force/velocity relationship for eccentric contractions suggests that the faster the contraction the greater the force levels at a set load, the loading during the partial ROM repetitions was more than that used during the full ROM tests. This extra loading may have presented the subjects with a mass that did not allow for a fast, controlled eccentric contraction. The fact that the subjects were unfamiliar with the lifting of a load greater than their full ROM 1RM may have resulted in the need to concentrate on stabilising the mass during the eccentric phase of the movement. However, the concentric phase of the movement was far quicker during the partial ROM repetitions than the full ROM tests. This suggests that the level of concentric loading, despite being greater than the loads the subjects were normally accustomed to, did not present a problem for their control of the movement. These factors combined suggest that partial ROM exercises with loads greater than full ROM 1RM results in a movement that emphasises eccentric control. However, whether this enhanced eccentric instability presented by the partial ROM exercise is affected by

VROM training warrants further investigation. This is because if the eccentric instability is reduced, greater velocities during the eccentric contraction can be performed leading to increased eccentric force production and greater overloading of the muscles. This form of training may result in greater eccentric strength throughout the ROM, potentially having a number of benefits. These include improved athletic performance and a greater ability to absorb impact during unplanned landings, for example falls, where high levels of eccentric strength are required to provide shock absorption.

2.2.4 Effects on Muscle Architecture

Another limitation on the movement specificity of full ROM resistance training is the effect of the restricted eccentric overload on muscle architectural adaptations such as fascicle length and pennation angle. Although the biochemical properties of muscles such as myosin ATPase activity have been found to be a major factor in potential shortening velocity of the musculature (Barany, 1967; Schluter and Fitts, 1994), previous research has found that muscle fascicle length is one of the most influential factors on the maximal shortening velocity of the muscle group (Burkholder, Fingado, Baron and Lieber, 1994; Sacks and Roy, 1982). While these earlier studies show the importance of fascicle length on performance, the pennation angle of the muscle fascicles may also affect the potential shortening velocity of the contractile unit (Kumagai, Abe, Brechue, Ryushi, Takano and Mizuno, 2000). This section will briefly discuss the role of muscle architecture on performance, followed by a discussion of the potential drawbacks of traditional full ROM training for promoting preferential architectural adaptations.

Fascicle Length and Pennation Angle

In terms of muscular performance, a lower resting pennation angle and longer fascicle length enhances the potential shortening velocity of the muscle group (Kawakami, Abe, Kuno and Fukunaga, 1995). To explain this phenomenon, an adaptation of the idealised model of muscle-tendon architecture presented by Kumagai *et al.*, (2000) is provided in Figure 2.4.

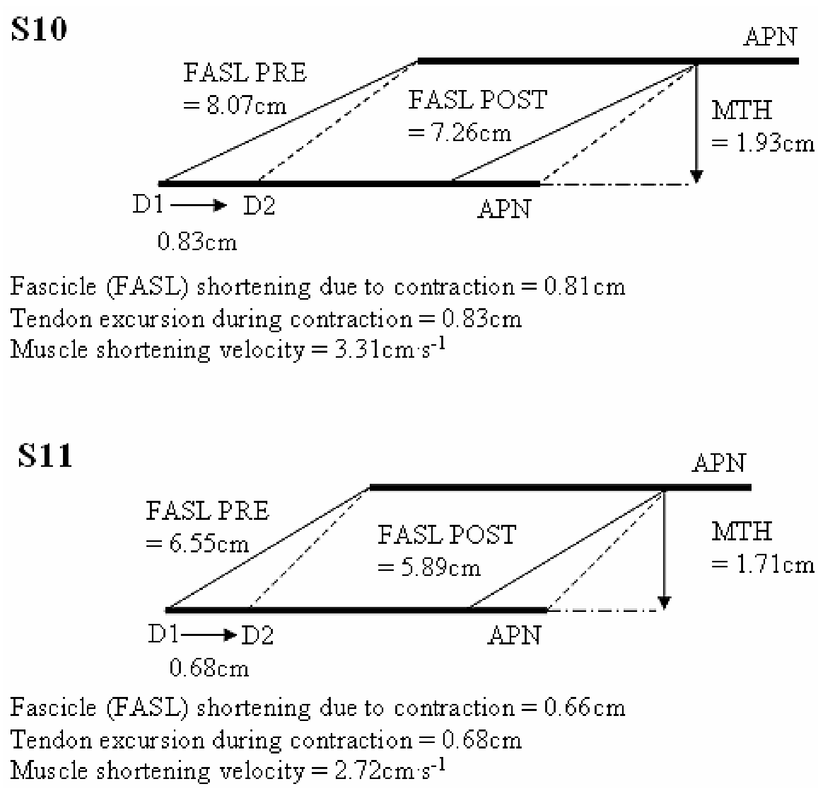

Figure 2.4. The relationship between fascicle length and shortening velocity.
A schematic illustration of the lateral head of the gastrocnemius, representing tendon excursion with fascicle shortening. Mean values of muscle thickness (MTH) and fascicle length (FASL) are taken from male sprinters with personal best 100m sprint times of 10.0 – 10.9 s (S10) and 11.0 – 11.7 s (S11). The thick, horizontal lines represent the two aponeuroses (APN), with FASL PRE representing fascicle length prior to contraction and FASL POST representing fascicle length after a 10% shortening of fascicle length. Assuming the same time for contraction, the longer muscle fascicles of the S10 group result in a shortening velocity of 3.31 $cm \cdot s^{-1}$, while the shorter muscle fascicles of the S11 group produce a slower shortening velocity of 2.72 $cm \cdot s^{-1}$. Adapted from Kumagai *et al.* (2000).

This model represents the gastrocnemius lateralis muscles of two groups of sprinters. The S10 group refers to the 22 professional sprinters in the Kumagai *et al.* (2000) study who recorded personal best 100 m sprint times between 10.0 and 10.9 seconds. The S11 group represents the 15 sprinters who recorded personal best times of between 11.0 and 11.7 seconds. The results of this study are presented in Table 2.1, however, for this example it is important to note that the fascicle lengths for the S10 group were significantly longer (8.1 $\pm$ 1.5 cm vs. 6.6 $\pm$ 0.7 cm) and the pennation angles significantly lower (14.0 $\pm$ 1.4^{o} vs. 15.2 $\pm$ 2.1^{o}) than those of the S11 group. When these factors were examined by the researchers it was revealed that the distance between the two aponeuroses of attachment for the S10 and S11 groups was 1.9 cm and 1.71 cm apart, respectively. It was also evident that the actual straight line displacement between the resting origin and insertion points was 8.07 cm and 6.55 cm for the S10 and S11 groups respectively.

Knowledge of these architectural properties allowed for a simplistic prediction of the shortening velocity of the muscle fascicles during a concentric contraction, which occurs when the fascicles pull the two tendons towards each other via the aponeuroses of attachment. This is achieved by the fascicles pivoting about their origin during the shortening of the muscle fascicle, which results in a subsequent increase in the pennation angle. Although the two tendons are coming towards each other, they still remain parallel whilst remaining the same distance apart (Narici, Hoppeler, Kayser, Landoni, Claassen, Gavardi, Conti and Cerretelli, 1996). In this model, Kumagai *et al.* (2000) assumed, based on the results of previous research, an average muscle shortening of 10% of fascicle length and a 250 ms duration of muscular shortening velocity (Andersen, Adams, Sjogaard, Thorboe and Asltin, 1985). When this change in fascicle length was applied to the model, trigonometry performed by the investigators revealed that the straight line displacement between the two aponeuroses of attachment was reduced by 0.8 cm and 0.7 cm for the S10 and S11 groups respectively.

When factoring in the 250 ms duration of muscular shortening velocity, this results in velocities of 3.3 $cm \cdot s^{-1}$ and 2.7 $cm \cdot s^{-1}$ for the S10 and S11 groups respectively. These calculations revealed a 23.5% greater potential shortening velocity for the S10 group in comparison with the S11 group. While a previous computer modelling study showed that changes in maximum force or neuromuscular activation produce greater changes in jumping performance than changes in muscle architecture (Nagano and Gerritsen, 2001), this dramatic difference in potential shortening velocity would appear to have a contributing effect on an athlete's explosive ability.

Furthermore, not only does possessing longer muscle fascicles and lower pennation angles have a beneficial effect on maximal shortening velocity, it also allows for more contractile tissue to be possessed by the athlete without increasing the anatomical cross-sectional area (ACSA) of the muscle group dramatically. For example, an athlete with long muscle fascicles who gains muscle mass would have the added mass spread along a greater length of muscle than an athlete with short muscle fascicles. Since the mass is spread across a broader region, it would not create as much muscle thickness in the belly of the muscle when compared to the muscle with shorter fascicles. This would result in less change to the pennation angle in the muscle with long fascicles, despite an identical increase in muscle mass. This suggests that possessing longer muscle fascicles not only provides the benefit of greater shortening velocity, but also reduces the negative effect of an increase of muscle mass on potential shortening velocity. These factors may combine to enhance the ability of an athlete to exert dynamic force.

Although this previous discussion has highlighted the benefits of long fascicles and low pennation angles for force production biased towards high velocities, in contrast, a greater angle of pennation may lead to an enhanced ability to produce force as the velocity decreases. Studies assessing the muscle architecture of bodybuilders, powerlifters, sumo wrestlers and athletes participating in sports biased towards low velocity force production have shown that they generally possess higher pennation angles and shorter muscle fascicles than untrained subjects, or those who participate in dynamic sports such as swimming and sprinting (Ichinose, Kanehisa, Ito, Kawakami and Fukunaga, 1998). A previously cited explanation for enhanced force production of muscles possessing higher pennation angles was that it may be due to a greater concentration of contractile protein per muscle group, due to increased muscle thickness. This may be because an increase in muscle ACSA results in greater pennation angles of the muscle fascicles (Ichinose *et al.*, 1998). As a muscle fibre undergoes hypertrophy, its ACSA increases and often takes on a more rounded muscle shape. This in turn leads to an increase in the pennation angle of the muscle fascicles, which creates a subsequent increase in the physiological cross-sectional area (PCSA) of the muscle.

Although ACSA provides a measure of the thickness of the muscle, PCSA provides a more direct measure of the muscle's force potential. PCSA is defined as the magnitude of muscle fibre area perpendicular to the longitudinal axis of the muscle fascicle multiplied by the cosine of the angle of pennation (Aagard, Andersen, Dyhre-Poulsen, Leffers, Wagner, Magnusson, Halkjaer-Kristensen and Simonsen, 2001; Maxwell, Faulkner and Hyatt, 1974; Wickiewicz, Roy, Powell and Edgerton, 1983). The relationship between pennation angle and PCSA is displayed in Figure 2.5.

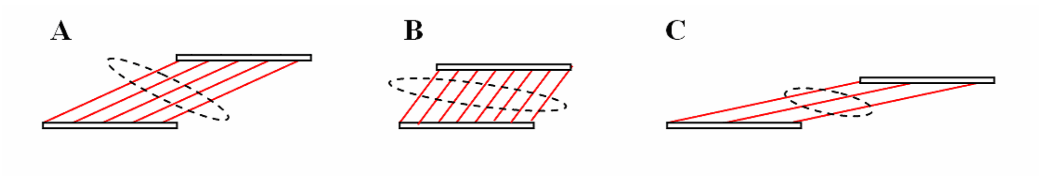

Figure 2.5. The relationship between pennation angle and PCSA.
As pennation angle increases, PCSA increases, resulting in potential shortening velocity decreasing and force increasing.
A Moderate pennation angle, moderate PCSA, moderate number of fascicles per longitudinal length of muscle.
B High pennation angle, high PCSA, high number of fascicles per longitudinal length of muscle.
C Low pennation angle, low PCSA, low number of fascicles per longitudinal length of muscle.

However, a potential drawback to increasing the PCSA of the muscle fascicles is an increase in intramuscular pressure. Previous studies suggest that the greater the fascicle angle and the shorter the fascicles length the higher the intramuscular pressure (Kawakami, Ichinose and Fukunaga, 1998; Miura, McCully, Nioka and Chance, 2004). This increased intramuscular pressure may inhibit the oxygenation of the muscles during exercise (Miura *et al.*, 2004). While the detrimental effects of this adaptation are minimal in sports that rely almost solely on anaerobic energy systems, such as weightlifting, the results for those athletes who participate in sports with high aerobic output or anaerobic waste production demands would be hindered by this adaptation. Therefore, in a typical athlete, an increase in muscle force with minimal effect on muscle PCSA and architectural features would appear to be most beneficial. This suggests that a training program that can offset an increase in pennation angle due to resistance training, while still increasing performance, may be optimal.

The Effects of Training on Muscle Architecture

Whilst muscle architecture appears to be an important determinant of performance, actual scientific studies in human subjects confirming changes in muscle fascicle length and pennation angles by measuring pre- and post- training interventions are scarce (Aagard *et al.*, 2001; Blazevich *et al.*, 2003; Blazevich, Gill, Deans and Zhou, 2007; Blazevich and Giorgi, 2001; Kawakami *et al.*, 1995; Rutherford and Jones, 1992). In a study performed by Blazevich and Giorgi (2001), ten subjects with at least one year of resistance training experience were split into two groups and assessed for muscle architectural response to a 12 week training program focussing on the upper body bench pressing movement. The experimental (EXP) group were injected with testosterone enanthate in a volume equal to 3.5 $mg \cdot kg^{-1}$ of their body mass. In contrast, the control (CON) group received a placebo injection. Assessment of bench press strength and the muscle architectural characteristics of the triceps brachii lateralis were performed pre- and post-intervention.

Despite the low subject numbers and statistical power (power = 0.34) of this study, a number of interesting findings were reported. With respect to muscle architecture, the results showed that both groups reported a significant increase in muscle thickness of the triceps brachii lateralis. Despite the EXP group being supplemented with testosterone, there was no significant between subject group difference in muscle thickness. However, the results of this study suggest that the actual mechanisms for the increase in muscle thickness were different between groups. Along with a greater increase in bench press strength, the EXP group reported a significantly larger increase in pennation angle. In fact, the CON group actually recorded slightly lower pennation angles post-intervention in comparison with their pre-training results. In contrast, the CON group reported a non-significant increase in muscle fascicle length, with the EXP group actually recording a slight decrease in fascicle length. However, these differences in pennation angle between groups may have been due to a number of factors. These factors could include a side effect of steroid administration, such as fluid retention, or measurement error inherent when performing an assessment of muscle architecture using low frequency ultrasound combined with a manual goniometer for assessment of pennation angle.

Although the results of this study are not conclusive, it does suggest that the training an athlete performs may have an effect on the architecture of the muscle. Data from cross-sectional studies suggests that changes in muscle fascicle length and pennation angles do occur depending on the subject’s contractile history (Kawakami, Abe and Fukunaga, 1993). These architectural features of the muscles differ markedly between groups of athletes, with high level sprinters possessing far greater muscle fascicle lengths and lower pennation angles than weightlifters and bodybuilders. These trends are outlined in Table 2.1, which is a review of the studies that have examined muscle architecture in sprinters (high velocity contractions), weightlifters (high force contractions), endurance athletes (low force) and sedentary individuals.

Table 2.1. A comparison of fascicle length/limb length (FL/LL) and pennation angle (PAN) of the vastus lateralis and gastrocnemius medialis in subjects with a variety of training backgrounds.

SUBJECTS	VASTUS LATERALIS		GASTROCNEMIUS MEDIALIS		STUDY
TRAINING STATUS	PAN (°)	FL/LL (cm/cm)	PAN (°)	FL/LL (cm/cm)	
Untrained: No recreational sports activity in prior 2 years (n = 24, mass = 58.6 ± 6.8kg, ht = 171 ± 6cm)	19.5 ± 3.6	0.18 ± 0.03	20.4 ± 2.5	0.14 ± 0.02	Abe *et al.*, 2000
Sprint 10: Professional sprinters, PB times 10.0 - 10.9 s (n = 22, mass = 66.3 ± 4.1kg, ht = 172 ± 4cm)	19.0 ± 3.2	0.22 ± 0.04	21.4 ± 2.9	0.17 ± 0.03	Kumagai *et al.*, 2000
Sprint 10: Elite male sprinters, PB times 10.0 – 10.9 s (n = 23, mass = 66.1 ± 3.9kg, ht = 172 ± 4cm)	18.5 ± 3.1	0.23 ± 0.04	21.5 ± 3.0	0.17 ± 0.03	Abe *et al.*, 2000
Sprint 11: Professional sprinters, PB times 11.0 - 11.7 s (n = 15, mass = 64.7 ± 6.4kg, ht = 173 ± 6cm)	21.1 ± 2.1	0.19 ± 0.02	23.5 ± 2.6	0.14 ± 0.02	Kumagai *et al.*, 2000
LWT: Light-weight class powerlifters, <67.5kg (n = 7, mass = 63.9 ± 5.6kg, ht = 159.9 ± 5.0cm)	25.6 ± 3.5	0.17 ± 0.02	25.9 ± 2.7	0.13 ± 0.02	Brechue and Abe, 2002
MWT: Middle-weight class powerlifters, 70 – 100kg (n = 6, mass = 78.4 ± 6.7kg, ht = 166.1 ± 5.7cm)	22.1 ± 4.2	0.20 ± 0.03	26.6 ± 2.3	0.12 ± 0.01	Brechue and Abe, 2002
HWT: Heavy-weight class powerlifters, >100kg (n = 7, mass = 135.1 ± 26.5kg, ht = 181.6 ± 6.6cm)	24.3 ± 4.9	0.21 ± 0.03	31.2 ± 3.7	0.13 ± 0.02	Brechue and Abe, 2002
Endurance: Elite 10km or marathon runners (n = 24, mass = 57.6 ± 4.3kg, ht = 172 ± 5cm)	23.7 ± 2.1	0.15 ± 0.02	23.3 ± 1.8	0.13 ± 0.02	Abe *et al.*, 2000

Before conclusions drawn from a comparison of results between different studies can be described, the inherent limitations of detecting small changes and/or differences in fascicle length and pennation angle must be discussed. A number of factors involved in the assessment of muscle architecture could have a major influence on the results achieved. These include, but are not limited to, the standardisation of the subject's testing position, the positioning of the ultrasound probe, the scanning frequency, the competency of the sonographer and the analysis protocol used. These factors make it very difficult to compare the results of independently performed studies, and the lack of reporting of the measurement error involved in these tests limits the potential to derive meaningful information.

Therefore, although these conclusions are influenced by the previously described factors, the studies used in this comparison all consisted of similar methodology and were performed by the same group of researchers. When comparing the high force athletes (weightlifters) with the high velocity athletes (sprinters) from these studies, the S10 and S11 groups from the Kumagai *et. al* (2000) study can be most accurately matched to the LWT group from the Brechue and Abe (2002) study. These three groups possessed similar body mass (S10 = 66.3 ± 4.1 kg, S11 = 64.7 ± 6.1 kg and LWT = 63.9 ± 5.6 kg), fat free mass (S10 = 61.6 ± 3.8 kg, S11 = 58.9 ± 5.1 kg and LWT = 55.2 ± 5.3 kg) and muscle thickness of the vastus lateralis (S10 = 2.75 ± 0.30 cm, S11 = 2.67 ± 0.32 cm and LWT = 2.83 ± 0.23 cm) and gastrocnemius medialis (S10 = 2.37 ± 0.37 cm, S11 = 2.25 ± 0.19 cm and LWT = 2.11 ± 3.4 cm). In contrast to these similar findings, the LWT group possessed a dramatically higher mean pennation angle for the vastus lateralis than the two groups containing sprinters, with a 34.7% and 21.3% greater pennation angle than the S10 and S11 groups respectively. A similar, though not as marked difference is also evident for the gastrocnemius medialis, with the LWT group recording a 21.0% and 10.2% greater angle than the S10 and S11 groups respectively.

This comparison shows that the muscle architecture of the weightlifters was dramatically different to that of the sprinters. When the results for the weightlifters, sprinters and untrained subjects are examined together, an assumption can be made about the effects of contraction history on muscle architecture. The results for the untrained subjects show that their resting pennation angles are similar to those of the high level sprinters, and much lower than those of the weightlifters. However, their fascicle length to limb length ratio is similar to those of the weightlifters but much lower than the results for the sprinters. These findings imply that efficient sprint training may result in elongation of the muscle fascicles with minimal effect on pennation angles. These results suggest that it is advantageous for ballistic athletes to possess long resting muscle fascicles and low angles of pennation for optimizing maximal shortening velocity of the muscle (Kumagai *et al.*, 2000). In contrast, for resistance training an increase in the pennation angle of the muscles with only a minor effect on the fascicle length to limb length ratio is required. Therefore, traditional weightlifting may have a detrimental effect on the potential shortening velocity of the muscle fascicles.

While these comparisons across subject groups in different studies are far from definitive, this notion is supported by the findings of a previous training study. Blazevich *et al.* (2003) demonstrated that a combined resistance and sprint training intervention increases the angle of pennation of the muscle fascicles, while having a minimal effect on muscle fascicle length, whereas speed training alone decreases the angle of pennation and dramatically increases the muscle fascicles length. In this study, eight female and 15 male subjects who had been participating in greater than three consecutive months of resistance training immediately prior to the study volunteered for a five week training intervention. The subjects were split into three groups to assess the effect of three different forms of training on muscle architecture and performance. The first group (RT) performed two sessions per week of resistance training consisting of 3 x 6 6RM squats on the heavy day, and 3 x 6 jump squats with 30-50% of isometric 1RM on the light day. The second group (HACK) performed the same loading protocol, however the exercise was unilateral front hack squats. Both of these groups also performed supplementary exercises to prevent muscle imbalances during these training sessions, as well as two sprint training sessions per week. The third group (SPRINT) performed four sprint training sessions per week and no resistance training sessions. Muscle architectural testing consisted of fascicle length, pennation angle and cross-sectional area assessment of proximal and distal portions of the vastus lateralis (VL) and rectus femoris (RF) of the right legs of the subjects using B-mode ultrasonography. Performance testing consisted of a wide variety of measures, ranging from 20 m sprint and single and double-legged vertical jumps to isometric squat strength, ballistic jump squats and isokinetic torque and position of peak torque at $30^{o}\cdot s^{-1}$. Testing was performed before and three days after the five week training intervention.

Although no significant differences in any of the performance variables were found, a number of interesting findings were reported in terms of the muscle architectural features. While the RT and HACK groups recorded similarly small, non-significant increases in both proximal and distal VL pennation angles, the SPRINT group recorded a significant decrease in distal VL pennation angle. In regards to the fascicle length of the VL, the SPRINT group showed a significant 81% and 25% post-intervention increase in fascicle length at the distal and proximal sites respectively. In contrast, the RT group recorded small, non-significant decreases in fascicle length at both sites. The HACK group also recorded a slight decrease in fascicle length at the distal site, and a minute increase in length at the proximal site.

These results suggest that concurrent full ROM resistance and speed training produces dissimilar and less velocity-specific beneficial architectural changes in comparison with speed training alone. Furthermore, it appears that resistance training in isolation produces unfavourable muscle architecture adaptations for sporting performance. However, numerous studies have shown that this method of training actually improves dynamic force production (Augusstson, Esko, Thomee and Svantesson, 1998; Fatouros *et al.*, 2000; Hakkinen, Kraemer, Newton and Alen, 2001). This can most likely be attributed to the increase in force production of the contractile components. While there is no doubt that traditional resistance training enhances the force production capabilities of the muscle by increasing the amount of contractile material attached to the tendon, it does appear to increase the pennation angle of the muscle fascicles while having a limited effect on fascicle length. However, the increase in force production may actually mask the adverse adaptations taking place on the muscle's architecture. Therefore, even though the muscle is becoming more mechanically inefficient, the enhanced neural response and/or ACSA and PCSA of the muscle can overcome these deficiencies.

The previous studies performed by Kumagai *et. al* (2000) and Brechue and Abe (2002) found that bodybuilders and Olympic lifters possess much greater pennation angles than sprinters and untrained subjects. This may be due to the greater ACSA of their muscles when compared with the untrained subjects. However, the ACSA of the lower limb muscles of the sprinters was comparable to that possessed by a number of the weight lifters. This may be explained by the fact that the athletes who train to become elite sprinters are likely to have a genetic profile that is biased towards ballistic power. They may naturally possess significantly lower pennation angles than the average person, and the increase in muscle thickness due to training may have increased their muscle's angle of pennation towards the typical untrained norm. Although this may be the case, it is also possible that the explosive nature of their training has enabled them to maintain their muscle's architecture in a state that optimizes shortening velocity while increasing muscle thickness, and therefore potential for force production. To support this theory, dynamic eccentric contractions are known to play a large role in the explosive plyometric movements, such as those performed during sprint training (Wilson, Murphy and Giorgi, 1996). These contractions have been previously suggested as a method of changing the resting lengths of the sarcomeres in a muscle fascicle (Proske and Morgan, 2001). This may also lead to an increase in fascicle length, with a subsequent reduction in pennation angle of the fascicle due to decreased intramuscular pressure.

Furthermore, the weight lifters also possessed much shorter muscle fascicles than the elite sprinters, and in the case of the gastrocnemius medialis, shorter muscle fascicles than the untrained subjects. Once again, whether this is due to genetics or method of training is unknown. However, as it would appear logical that muscle architecture would adapt positively to the stimulus imposed, an adaptation resulting in increased PCSA via an increase in pennation angle would appear to be optimal for lifting heavy loads at low velocities. In contrast, the additional leverage benefit of high pennation angles and short muscle fascicles would appear to be optimal for lifting heavy loads at low velocities. Consequently, it is logical to assume that the muscles would adapt in a way to promote this mechanism. However, in most sports the demands placed on the athlete are not solely biased towards one extreme of the force-velocity spectrum. In reality, they are often varied and require both high force and high velocity contractions. Furthermore, eccentric contractions also play a major role in a number of sporting movements and injury prevention strategies of the musculotendinous system. Therefore, training methods that result in muscle fascicles that are capable of both high force and high velocity movements, in addition to being prepared for intense eccentric contractions, would be of benefit to some athletes. Despite being a resistance training exercise with a high force component, performing VROM exercises may result in these adaptations because of the extra eccentric overloading placed on the muscle groups. Furthermore, the intensity of the stretch shortening cycle (SSC) movement during VROM training may also affect the architecture of the muscle.

Previous research by Ishikawa and Komi (2004) has revealed that as the intensity of the countermovement increases, the architecture of the musculotendinous unit changes dramatically. This study revealed that increased countermovement intensity actually reduces the relative stretching of the muscle fascicles during the braking phase, with increased EMG activity during the pre-stretch and braking phases enhancing the stiffness of the musculotendinous system (Ishikawa and Komi, 2004).

To counter this increased rigidity of the contractile elements, the lengthening of the tendon itself increases, which results in augmentation of the elastic energy supplied by the tendinous tissue. Based on this mechanism, it would appear that the contractile properties ability to perform the quasi-isometric contraction necessary during countermovements is paramount. Therefore, to perform intense countermovements in sports or activities of daily living, the ability of the muscle to control its eccentric lengthening would be a determining factor in SSC performance.

Due to the greater than full ROM 1RM loads, and varied positions of the countermovement during VROM training, this method of training may increase countermovement performance in the ROM where SSC movements are often performed. This may potentially lead to an adaptation in the architectural properties of the muscle, such as increased fascicle length, that enhances the ability to perform eccentric contractions.

Furthermore, performing VROM training may result in architectural adaptations that allow for efficient concentric activation to occur at different stages of the ROM. Previous research shows that motor units are activated in accordance with their mechanical efficiency of leverage during exercise (Ter Haar Romeny, *et al.*, 1982; Ter Haar Romeny, *et al.*, 1984). Therefore, the performance of VROM training may lead to both architectural and neural adaptations that result in more efficient, and powerful, concentric contractions throughout a limited ROM. However, no previous research has examined the effects of partial or VROM training on muscle architecture.

2.3 PROGRESSIVE OVERLOADING

These previous sections have discussed the limitations of full ROM resistance training, and the potential for VROM training, in regards to different components of movement specificity. Another principle of resistance training that appears restricted by full ROM resistance training is the ability to progressively overload an athlete. Although there are a number of factors that can be modified to ensure progressive overloading of the athlete, this section of the literature review will focus on the limitations of full ROM resistance training for modifying the intra-session volume of training. The aim of this section of the literature review is to explore two factors that are limited by traditional full ROM resistance training. These are:

1. Increasing the load or resistance
2. Performing more repetitions with a given load

2.3.1 Increasing the Load or Resistance

The load prescribed can have a dramatic effect on the results of a resistance training program. The acute effects on metabolic, hormonal, neural and cardiovascular responses may vary depending on the loading protocol incorporated (Collins, Hill, Cureton and Demello, 1986; Craig and Kang, 1994; Kraemer, Marchitelli, Gordon, Harman, Dziados, Mello, Frykman, McCurry and Fleck, 1990; McCall, Byrnes, Fleck, Dickinson and Kraemer, 1999). Furthermore, the longitudinal effects on strength, strength endurance, muscle hypertrophy and metabolic adaptations are also dependent on the loading protocol prescribed during training (Kraemer *et al.*, 2002).

While a wide variety of loads have been used in previous training studies to enhance strength levels, it appears that for experienced lifters a load of between 1-

6RM, or between 80-100% of 1RM, is most effective for increasing dynamic muscle strength (Berger, 1962; Kraemer *et al.*, 2002; Weiss, Coney and Clark, 1999). Furthermore, for a long-term training program it is essential to prescribe a periodised scheme of training loads within this range to ensure that the risk of reaching performance plateaus is minimised. This is where full ROM training reveals its limitations, given that the range of suitable loads is quite restricted. For example, according to the proposed guidelines an advanced trainer with a 1RM bench press of 120 kg would be restricted to a loading protocol of between 96 kg and 120 kg. This allows a range of 24 kg for loading, possibly enough to prevent plateaus. However, if the same trainer has a 1RM single arm bicep curl of 30 kg then the loading range is only from 24 kg to 30 kg. Considering that there are often minimal increments of 2.5 kg in a gym setting, this would only allow for three possible loads within this range. To prevent plateaus using full ROM training, the athlete may then have to resort to lifting lighter loads. However, as previously discussed (see Section 2.2.1), this can reduce the intensity of the exercise and result in large deceleration phases, therefore negating many of the potential benefits of resistance training.

2.3.2 Performing More Repetitions with a Given Load

If the athlete is limited in terms of modifications to the load lifted during a training program, another method of increasing volume of work is to perform more repetitions with a given load. While the ability to perform more repetitions with a set load is an obvious indicator of increased strength levels, achieving this can be difficult for an experienced trainer. Previous research has shown that the number of repetitions that can be performed with a specific load, especially once the load approaches maximal, is directly related to the absolute strength of the athlete (Morales and

Sobonya, 1996). Therefore, to perform more full ROM repetitions with a given load, the athlete must continuously increase their absolute strength level, which becomes exponentially more difficult as the athlete's training experience increases.

2.3.3 Overcoming the Progressive Overloading Limitations

These limitations for increasing the volume of work during full ROM resistance training may be reduced dramatically by performing VROM training. While the loading during the concentric phase of the movement is still limited to the athlete's 1RM, this 1RM varies depending on the ROM trained during VROM training. For example, if an athlete capable of bench pressing 100 kg is to perform four sets at 80% of their 1RM during full ROM training, each set would be performed with 80 kg. However, if four VROM training sets were performed with 80% of 1RM for each ROM, each loading condition would be different. While the full ROM set would still be performed with 80 kg, the partial ROM sets would actually be performed with loads exceeding their full ROM 1RM. Previous studies have shown partial ROM bench press 5RM strength to be 17.6% higher than full ROM bench press (Mookerjee and Ratamess, 1999). This study defined a partial repetition with a countermovement performed when the elbow flexion angle reaches 90^{o}. The isoinertial strength differences as the ROM becomes smaller are likely to be even more distinctive, although this has not been previously assessed.

While the loading may be increased, the actual work performed during the session may remain similar to the full ROM training session. This is because the load displacement is much smaller. Although the partial ROM exercise requires less actual movement of the bar, the time it takes to perform a repetition has been previously shown to be similar to the full ROM exercise (Mookerjee and Ratamess, 1999). However, this was speculated to be a result of unfamiliarity with the load used during lifting, and may change once the subject becomes familiarised with the training protocol. Although there is the potential for VROM training to allow for increases in the volume of training performed, no previous studies have assessed the volume differences between partial and full ROM training sessions.

2.4 VARIABLE ROM TRAINING: PREVIOUS RESEARCH

The previously mentioned factors suggest that performing VROM training may be superior to full ROM only resistance training. While the potential benefits of VROM training are evident, there have been no previous studies assessing this method of resistance training. However, performing partial ROM training has received attention in previous literature. This partial ROM training consists of the athlete only performing sets of an exercise in a specified ROM. In the case of rehabilitation, the movement is often limited to the pain-free ROM. In contrast, for resistance training purposes it is often the athlete’s strongest ROM for each exercise that is trained. A number of magazine articles, non-scientific journal articles and even entire books have been written purporting the potential of partial ROM training in the strongest ROM (Bloomfield *et al.*, 1994; Scheett, 2003; Sisco and Little, 1997; Zatsiorsky, 1995). However, the number of empirical studies is very limited. The following section will discuss the results of these studies with respect to their effects on performance.

2.4.1 Previous Studies Examining Partial ROM Training

One of the most extensive studies performed in the area of partial ROM training was performed by Graves *et al.*, (1989). The researchers investigated the specificity of limited ROM variable resistance training in 59 young, untrained subjects (male = 28, female = 31). These subjects were randomly split into four groups. The control (CON) group did not perform any training. The flexion group (FLEX) performed knee extensions in a ROM limited to between 120^{o} and 60^{o} of flexion. This corresponds to performing partial ROM training at long muscle lengths. The extension (EXT) group performed the knee extension in a ROM limited to between 60^{o} and 0^{o} of flexion, corresponding to performing partial ROM training at short muscle lengths. The full (FULL) group performed the knee extensions throughout the entire ROM.

All training for this study was performed on a Nautilus^{TM} variable resistance knee extension machine, with the intervention consisting of 10 weeks of single set training either two or three days per week. During the set the subjects were required to lift a maximal load that only allowed for between seven and ten repetitions to be performed, and was adjusted accordingly in the subsequent sessions. The repetitions were performed in a slow, controlled manner, with two seconds required for positive work and four seconds for negative work. Testing consisted of pre- and post-intervention isometric strength tests at eight knee joint angles. These positions were 9^{o}, 20^{o}, 35^{o}, 50^{o}, 65^{o}, 80^{o}, 95^{o} and 110^{o} of knee flexion using a Nautilus^{TM} knee extension tensiometer. The results of this study revealed a ROM specific adaptation in strength levels, with figures of each force curve compared to the control group provided in Figures 2.6, 2.7, and 2.8.

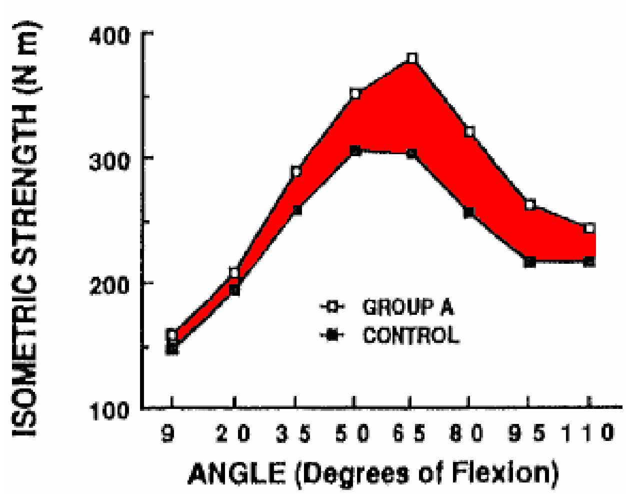

Figure 2.6. **A comparison of the results for the non-training (CONTROL) and partial ROM training at long muscle lengths (Group A - FLEX) groups from the Graves *et al.* (1989) study.**

The red shading between the lines is provided by the current author for comparison of force/ROM curves with Figures 2.6 and 2.7. Notice that at low flexion angles, corresponding to short muscle lengths, there is very little difference between the control and training groups, but within the trained ROM the difference is distinct.

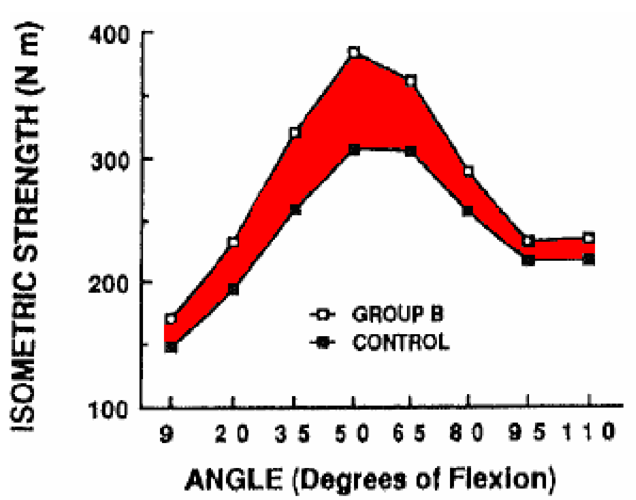

Figure 2.7. **A comparison of the results for the non-training (CONTROL) and partial ROM training at short muscle lengths (Group B - EXT) groups from the Graves *et al.* (1989) study.**

Notice that the force curve is in opposition to that of the FLEX group. In this comparison, at large flexion angles, corresponding to long muscle lengths, there is very little difference between the training and control groups, but at low flexion angles, corresponding to the trained region, the difference is quite noticeable.

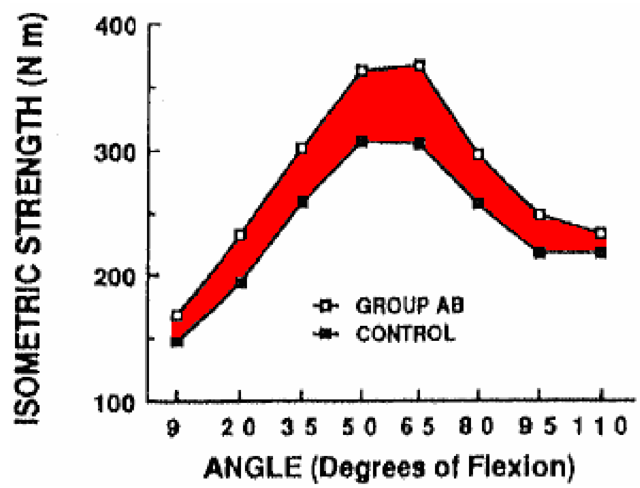

Figure 2.8. A comparison of the results for the non-training (CONTROL) and full ROM training (Group AB - FULL) groups from the Graves *et al.* (1989) study.
Notice that the characteristics of the force curve are almost identical to that of the CONTROL group, only with higher force levels. Figures 2.6., 2.7. and 2.8. are adapted from Graves *et al.* (1989).

The FULL group's intervention resulted in significantly greater increases in strength levels at each of the different joint angles in comparison with the CON group. Furthermore, it also provided greater adaptations at 95° of flexion when compared with the EXT group and at 20° when compared with the FLEX group. This suggests that the strength gains from partial ROM training are not as beneficial when strength is required outside of the trained ROM. However, whereas the FULL group only showed significantly greater improvements in performance enhancement at one joint angle when compared to each partial ROM intervention, when the FLEX and EXT groups were compared there were far more dramatic results. The EXT intervention resulted in significantly greater strength gains than the FLEX group at three joint angles, 20°, 35° and 50°. In contrast, the FLEX group reported significantly greater strength enhancement than the EXT group at two joint angles, 80° and 95°. Of further interest is that the EXT intervention did not result in significantly greater strength gains at 95°, which is outside the ROM trained, when compared with the CON group. A similar result was also reported for the FLEX group, which did not result in significantly different strength gains at 20^{o} or 9^{o} when compared with the CON group. The findings of this study suggest that partial ROM training may skew the force curve to favour the ROM trained. Although the full ROM training resulted in an increase in strength throughout the entire ROM, the effects were not as large as those of the partial ROM interventions in the phase of the movement that was trained.

Another interesting finding of the above study was that the EXT intervention, which involved training in the strongest ROM, resulted in a significantly greater increase in the load lifted at the end of the training intervention. The subjects in this group began training with a load of 52.1 $\pm$ 13.6 kg. At the end of the 10 week intervention the load lifted had increased to 84.7 $\pm$ 19.2 kg, a relative increase of 65.1%. In contrast, the FULL and FLEX groups only managed relative increases of 38.9% and 45.9% respectively. Similar findings to these were reported in a study assessing the effects of partial ROM training on lumbar extension strength (Graves *et al.*, 1992). This study also reported greater increases in the weight lifted during training in the group that performed partial repetitions in the strongest ROM, however these results did not reach significance.

Taken together, the results of the above two studies suggest that training with partial ROM exercises in the strongest ROM results in sizeable increases in the load which is able to be lifted. This rapid increase in strength may be beneficial for the athlete attempting to progressively overload their training program. If the athlete is experiencing a plateau in strength gains from full ROM training, performing partial

ROM exercises may allow for increasing either the load lifted or the number of repetitions performed by the involved musculature, which are two key aspects of progressive overloading.

While these studies show the potential for partial ROM training, a study performed by Massey, Vincent, Maneval, Moore and Johnson (2004) contained the most comparable training intervention to VROM training. In this study, 56 male recreational weightlifters participated in a two sessions per week bench press training intervention of a 10 week duration. The subjects were split into three groups. The first group (N=11, FULL) trained with three full ROM sets per session. The second group (N=15, PAR) performed three partial ROM sets per session. The third group (N=30, MIX) performed two partial ROM sets and one full ROM set per session for the first five weeks. In contrast, for the final five weeks of the study the MIX group performed one partial ROM set and two full ROM sets. Testing for all groups consisted of full ROM 1RM bench press strength, assessed pre- and post-intervention.

Although the investigators reported that there were no significant differences in performance gains between the three groups, the vast number of flaws in the methodology and statistical analysis severely limit the findings of this study. The three groups were uneven not only in subject numbers but also in strength levels. The pre-test 1RM strength levels of the three groups were 75.6 kg, 80.0 kg and 93.4 kg for the FULL, PAR and MIX groups respectively. This shows that the MIX group was already 23.5% stronger than the FULL group at the start of the study. Given that the subjects had no standardised strength training background, this could mean that those subjects in the MIX group had a more extensive training history. Consequently, they would be unlikely to experience as dramatic a change in strength as the lesser trained subjects. In fact, the methodology does not even state that the subjects were randomly assigned to groups. Furthermore, due to the very low levels of strength apparent in the groups in this study, it would appear that the potential for these subjects to achieve strength gains, regardless of the training intervention, was very high. In an attempt to justify their study, the investigators performed an ANCOVA on the results of the study. This analysis revealed a significant pre-test difference in strength levels of the three groups at $p<0.001$. The authors also performed t-tests on the pre- to post-intervention results of the study despite the uneven initial strength levels.

In terms of the training interventions, the only attempt to equalize work performed during the sessions was to assign an even number of sets to each group. However, due to the limited ROM trained in the PAR and MIX groups, the different loads lifted and the differences in initial strength levels, it appears that the work performed during each session would have been dramatically different between the three groups. This difference in work performed, in combination with the subject's low strength levels, would have had a considerable effect on the potential for strength gains in the subjects. Furthermore, the actual performance of the partial ROM training was not well explained. The method employed to control the ROM would have had a dramatic effect on the eccentric overloading and SSC component of the lift. For example, if traditional stoppers were used, the subject may lower the barbell until it touches the stoppers and then concentrically lift it back to terminal extension. This would limit the necessity for eccentric control of the load, one of the primary potential benefits of VROM training as discussed previously in this review of literature.

While the number of methodological flaws in this study limit its findings considerably, the fact that all three training methods resulted in full ROM strength gains for the involved subjects suggests that partial ROM training does result in transferability of strength gains outside the ROM trained. This transferability of strength gains supports the findings of a number of previous studies (Ayalon, Ben Sira and Tirosh, 2000; Barak *et al.*, 2004; Graves *et al.*, 1992).

However, the findings of Massey *et al.* (2004) are in contrast to those reported in another more recent study. Massey *et al.*, (2005) reported that full ROM training was more effective for increasing strength than partial or mixed ROM training. The methodology for this study was identical to that performed in the Massey *et al.* (2004) study. However, in the later study female subjects with very little training experience were used as subjects. Once again, the same methodological flaws limit the findings of this study.

2.5 Summary

While some of the above studies provide an interesting insight into the effects of VROM training, it is obvious that the results are far from conclusive. One of the major inadequacies of the previous research is that no studies have examined partial or VROM training in one of the groups that would appear to benefit the most: athletes. Further research examining force curve characteristics, performance and muscle architecture following a VROM intervention in trained subjects would provide information as to whether this method of training provides the potential for enhanced sporting performance.

2.6 Prologue to Experiments One, Two and Three

As previously mentioned in Section 1.4., to experimentally determine the effects of a VROM training program two factors must be assessed. These factors, along with a brief description of the experimental steps undertaken for their assessment, are:

1. *It must first be determined if the exercises performed during a VROM training session provide intra-session advantages.*

A primary proposed benefit of VROM training is an increase in peak force levels during the limited ROM sets. Theoretically, this would be partially due to an increase in the external loading which can be lifted by the athlete. Although previous research, which was reviewed in Section 2.4.1, has provided some limited evidence of these benefits, no prior studies have specifically examined the loads lifted, force produced and concentric work performed during VROM training.

Therefore, Experiment 1 is an examination of the force and work profiles of a VROM bench press training session. This step provides important information in regards to some of the benefits of VROM training. However, based on the findings of previous research, along with mechanical leverage principles that suggest a higher load can be lifted in the proposed limited ROM, the aim of this study was to determine the magnitude of the increases in load lifted and force levels in the limited ROM sets instead of determining whether there was actually any difference.

2. *If VROM resistance training is shown to provide within-session benefits, it must be determined if this method of training provides longitudinal performance gains when compared to a traditional full ROM resistance training program. If there are differences in performance, it must also be determined what the actual mechanisms behind these adaptations are.*

While the results of Experiment 1 provide important information relating to VROM training, the primary goal of this thesis was to examine the effect of a longitudinal VROM training program on functional performance. A secondary aim was to determine the mechanisms behind any differences in performance between this method and traditional full ROM training. One of these proposed mechanisms was a change in muscle architecture to enhance force production in the midrange of the movement. As previously mentioned in Section 2.2.4, numerous studies have examined muscle architecture in the lower limb and related this to performance. However, no prior studies have attempted to determine the relationship, if any, between upper body muscle architecture and functioning in a range of multi-joint performance tests. Therefore, Experiment 2 is an examination of the relationship between muscle architecture of the triceps brachii and upper body strength, power and musculotendinous stiffness.

Finally, Experiment 3 is a comparison of the effects of a 5-week VROM or full ROM training intervention on upper body performance in professional athletes. This study is the primary focus of this thesis, and attempts to provide an experimental examination of the global hypothesis.

Chapter 3

EXPERIMENT 1:

An Examination of Strength and Concentric Work Ratios During Variable ROM Training

3.1 ABSTRACT

No previous studies have examined the effect of variable ROM (VROM) training on peak force, load lifted and concentric work. Six male subjects with resistance training backgrounds (age: 20.2 ± 1.3 yr, height: 179.4 ± 4.6 cm, mass: 89.6 ± 9.9 kg, 6RM bench press: 92.5 ± 14.3 kg) participated in this study. Testing consisted of 6RM bench press strength tests during full (FULL), three quarter (3/4), one half (1/2) and one quarter (1/4) ROM from full elbow extension bench press, performed on a Smith machine. The 6RM load, peak force (PF) and concentric work (W) performed during each ROM was examined using a one-way ANOVA with an alpha level set at $p<0.05$. The 6RM load increased significantly as the ROM was decreased for all tests (FULL = 92.5 ± 14.3 kg, 3/4 = 102.1 ± 14.3 kg, 1/2 = 123.3 ± 23.6 kg, 1/4 = 160.9 ± 26.2 kg). The PF during each test was significantly higher during the 1/4 (1924.8 ± 557.9 N) and 1/2 (1859.4 ± 317.1 N) ROM from full elbow extension bench press when compared to the 3/4 (1242.2 ± 254.6 N) and FULL (1200.5 ± 252.5 N) ROM exercise. Although higher force levels were evident, the restriction in barbell displacement resulted in a subsequent reduction in W as the lifting ROM was reduced. These results suggest that VROM resistance training may provide intra-session benefits, due to enhanced movement specificity and force

production. Therefore, the effectiveness of this method of training for athletes participating in sports that require high force production should be explored.

3.2 INTRODUCTION

A number of potential benefits of VROM training have been proposed in the preceeding chapters, with two of the fundamental benefits being the production of peak force levels throughout different phases of the ROM and an increase in the load lifted by the athlete in the limited ROM sets. Whether these benefits actually occur is unknown, however, previous research suggests that performing limited ROM exercises with loads in excess of full ROM 1RM does not dramatically slow down the concentric phase of the movement (Mookerjee and Ratamess, 1999). Based on these findings, if a heavier load is lifted with a similar velocity profile the subsequent force output will be increased. Therefore, the potential for VROM training to augment force throughout the ROM appears plausible, however no previous research has examined this theory.

3.2.1 Statement of the Problem

The performance of VROM resistance training may provide superior benefits when compared to full ROM training. However, no previous studies have examined the peak force, concentric work or load lifted during this method of training.

3.2.2 Experiment Specific Hypotheses

Based on the findings of Mookerjee and Ratamess (1999), and the mechanical leverage benefits inherent during the partial ROM sets, it is hypothesised that a reduction in the ROM of the exercise will result in:

1. A significant increase in the load lifted due to favourable musculoskeletal mechanics.
2. A significant increase in peak force due to a combination of an increased external load and minimal effect on acceleration.
3. Despite the higher load lifted, concentric work will be significantly reduced as the ROM is restricted, due to a decrease in the displacement of the barbell.

3.2.3 Limitations

1. Measurement of force using a position transducer, which does not provide a direct measure of muscle force production.
2. The need to perform the exercise in a Smith machine, which hinders the application of the results to free weight training.
3. Performance of testing over two separate days, which may result in strength changes due to factors such as the level of fatigue.
4. The inability to control the exact position of the countermovement.

3.2.4 Delimitations

1. The subjects possessed resistance training experience, and therefore the results of this study are only applicable to a similar population.

3.3 METHODOLOGY

3.3.1 Subjects

Six male subjects (age: 20.2 $\pm$ 1.3 yr, height: 179.4 $\pm$ 4.6 cm, mass: 89.6 $\pm$ 9.9 kg) volunteered to participate in this study. The subjects were required to have a minimum of six months previous resistance training experience, with all subjects participating in a four week resistance training program prescribed by the primary investigator in the lead up to this experiment. Although the subject numbers were small, based on the results of a partial ROM training study performed previously by Mookerjee and Ratamess (1999) this number of subjects would still allow for high statistical power (P>0.80). This study received ethical approval from the Central Queensland University Human Research Ethics Committee (approval number H05/09-105).

3.3.2 Equipment

The strength testing was performed on a Smith machine (Calgym, Australia), with a digital rotary encoder (IDM Instruments, Australia) recording the position of the barbell throughout the movement. Knowledge of the mass of the bar, along with the displacement and time data acquired from the rotary encoder, allowed for determination of force output using a custom written Labview (National Instruments, U.S.A.) software acquisition and analysis package sampling at 1000Hz. Although this method of assessing force production does have limitations (Hori, Newton, Nosaka and McGuigan, 2006), it was deemed suitable based on the requirements of this study.

3.3.2 Experimental Protocol

Data collection consisted of two separate days of 6RM bench press strength testing, with the sessions separated by 72 hours. The first session consisted of 6RM bench press strength throughout the full and ¾ ROM from full elbow extension. The second session consisted of 6RM strength tests throughout ½ and ¼ of the ROM from full elbow extension. A 6RM strength test was used, in contrast to a higher load/lower repetition maximum test, because the loads during the limited ROM tests were expected to be far in excess of the load lifted during the full ROM test. Therefore, a 6RM test was chosen because it provided a test of maximal strength which did not place excessive unaccustomed strain on the subjects.

During the four week resistance training program leading up to this study, the subjects had performed four sessions of VROM bench press training. This was included into the subject’s training program to provide both familiarisation with the testing protocol and an approximation of the loads lifted during each ROM. Although this familiarisation was performed, it was still deemed necessary to split the testing into two separate sessions to prevent excessive fatigue from influencing the results of the study. Furthermore, although a cross-over design was considered for testing order, the subject’s extensive familiarity with full ROM bench press resulted in this test being performed in the first session. This familiarity allowed for an accurate prediction of the subject’s 6RM full ROM strength, reducing the number of tests performed before the actual 6RM load was determined. This reduced the potential for delayed onset muscle soreness during the second testing session.

The actual 6RM bench press strength tests were performed inside the Smith machine, with metal stoppers used to restrict the vertical plane of the movement in an attempt to limit the ROM during each set. The subject’s ROM could not be exactly limited to each ROM because of the 7.5 cm distance between stopper positions, however, this distance between settings still allowed for restrictions to the ROM that may be encountered during a typical VROM training session. Prior to testing the subject's hand positioning was determined and measured, with all tests performed using the same hand spacing position.

The tests were commenced with the subject lifting the barbell off the Smith machine supports, before pressing the barbell until full elbow extension was achieved. This phase of the movement was assisted during the partial ROM tests in an effort to reduce the stress placed on the subject's wrist joint. During performance of the testing repetitions the subjects were instructed to lower the barbell at a moderate pace until it reached a position slightly above the stoppers, at which point the investigator instructed the subject to perform a countermovement and lift the barbell as powerfully as possible. Lifting velocity was not controlled during the testing procedure. This countermovement position resulted in no contact between the barbell and stoppers, ensuring the integrity of elastic energy contribution during the countermovement.

An estimate of the subject's 6RM strength in each ROM was determined based on the loads lifted during training, and these estimated loads were used as a baseline for the strength tests. A warm-up set of six repetitions using 75% of this predicted 6RM was performed prior to the test. If necessary, after the 6RM test was performed the load was adjusted and repeated until the subject's 6RM for that specific ROM was determined.

3.3.4 Data Analysis

The 6RM strength for each VROM set was recorded by the investigator. Before any further data analysis was performed the displacement data was filtered using a 10 point moving average, which as discussed in Appendix A, is one of the most effective methods of filtering data in the time domain. Peak force was then assessed during the concentric phase for each trial. Force was assessed based on the equation:

F=MA

Where F = Force (N), M = Mass of the external load (kg) and A = Acceleration with correction for gravity ($m \cdot s^{-1}$), which was based on the displacement and time data received from the position transducer.

In addition, the concentric work performed during each repetition was examined using the formula:

W=FD

Where W = Work ($N \cdot m^{-1}$), F = Average force throughout the movement (N) and D = Total concentric displacement of the barbell (m). The mean value for concentric work performed per repetition was then normalized as a percentage of the concentric work performed during the full ROM bench press. This concentric work per repetition value is an important control variable for standardising the training programs during a longitudinal study.

3.3.4 Statistical Analysis

For each of the parameters of interest, a one-way ANOVA was performed on the results, which examined the effect of each ROM on the performance variable. All statistical analysis was performed using SPSS Version 14.0 (SPSS, U.S.A.). Confirmation of data sphericity (lower-bound epsilon >0.75) and equal variance (Levene Median Test) was performed prior to the analysis. The alpha level was set at $p<0.05$, with Fischer's Least Significant Differences (LSD) *post hoc* tests performed in the event of a significant main effect or interaction. The effect size of the analysis is represented by the R^2 value.

3.4 RESULTS

The results for 6RM strength are provided in Figure 3.1. Statistical analysis revealed a significant (F=129.77, $p<0.001$, $R^2=0.82$) main effect for testing ROM. *Post hoc* contrasts revealed that as the ROM decreased, the load lifted increased significantly ($p<0.01$ for all contrasts).

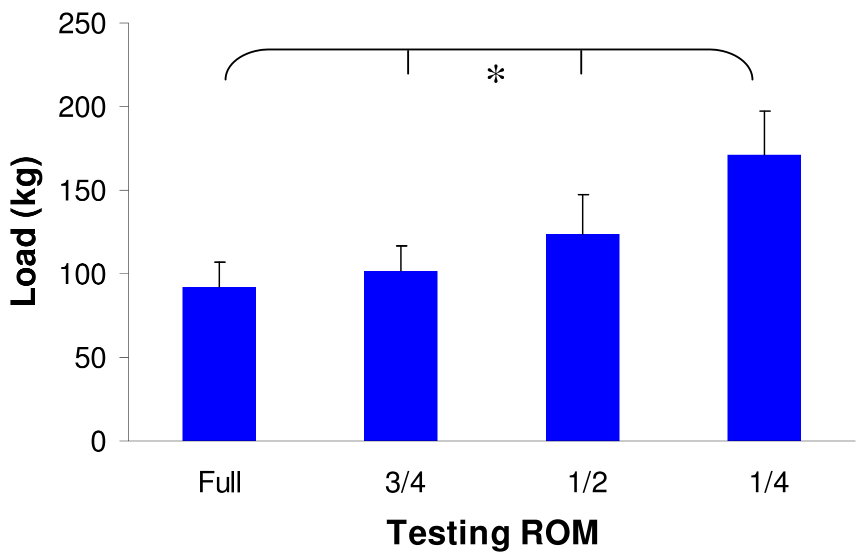

Figure 3.1. 6RM bench press strength in each ROM.
* Indicates a significant difference ($p<0.05$).

A significant main effect (F=14.73, $p=0.007$, $R^2=0.80$) for peak force in each ROM was observed. *Post hoc* contrasts revealed that both the ½ and ¼ ROM sets produced significantly higher peak force levels than the full ($p<0.001$ and $p=0.015$ for ½ and ¼ ROM respectively) and ¾ ROM ($p<0.001$ and $p=0.024$ for ½ and ¼ ROM respectively) tests. There were no significant differences in peak force levels between the full and ¾ or ½ and ¼ ROM tests. These findings are provided in Figure 3.2.

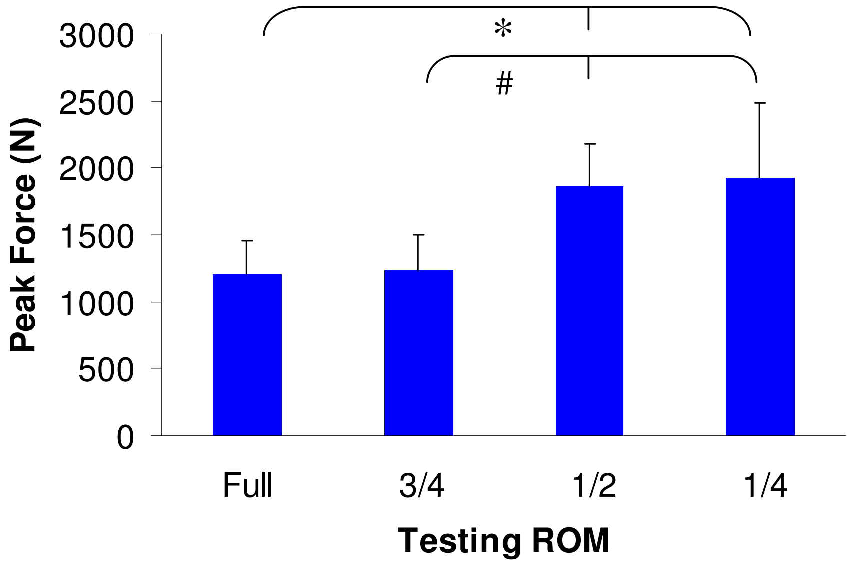

Figure 3.2. **Peak force during 6RM bench press in each ROM.**
* Indicates a significant difference (*p*<0.05) between the full ROM and the ½ and ¼ tests.
# Indicates a significant difference (*p*<0.05) between the ¾ ROM and the ½ and ¼ tests.

Figure 3.3 provides the mean concentric work per repetition performed for each VROM set. A significant (F=181.36, $p<0.001$, $R^2=0.83$) main effect for ROM was observed. Although the load lifted increased, *post hoc* contrasts showed that concentric work significantly ($p<0.05$) decreased for each test as the ROM was restricted, due to a decrease in barbell displacement.

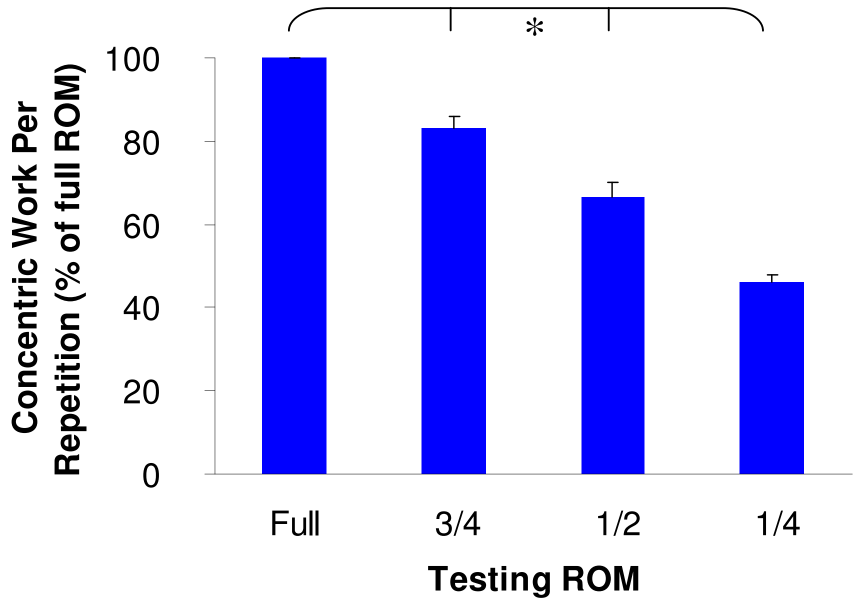

Figure 3.3. **Concentric work per repetition (as a % of full ROM concentric work) performed during each VROM set.**
* Indicates a significant difference (p<0.05).

3.5 DISCUSSION

The results of this study revealed that both the load lifted and the peak force output increased as the ROM of the bench press exercise decreased towards terminal elbow extension, in accordance with Hypotheses 1 and 2. These findings are reinforced by the previous study performed by Mookerjee and Ratamess (1999), which found that concentric velocity did not decrease dramatically during partial ROM exercises, despite an increase in the load lifted. In accordance with Hypothesis 3, despite the dramatically increased load which can be lifted during the partial ROM movement, there is still a significant decrease in concentric work due to the reduced displacement of the barbell.

Although no previous training studies have examined the use of VROM training, the results of this study suggest that it does provide intra-session benefits, which if used in a long-term training program, may invoke longitudinal performance gains. Theoretically, VROM training may better prepare the athlete for performance throughout the entire ROM by overcoming some of the limitations associated with full ROM resistance training. Examples of these problems include terminal deceleration, the limited ROM in which peak force is produced and the single countermovement position during traditional full ROM exercises (Elliott *et al.*, 1989; Lander *et al.*, 1985; Newton *et al.*, 1996; Young *et al.*, 2001).

To further explain these points, one of the major limitations of full ROM resistance training is terminal deceleration towards the end-range of the movement. While this can be overcome to some extent by incorporating ballistic exercises into the program (Newton *et al.*, 1996), this still does not result in peak force levels occurring in the ROM where high force production is often necessary during sport. By incorporating VROM training into a resistance training program, peak force levels in excess of those that occur during full ROM training are produced throughout the midrange of the movement. Therefore, a potential combination of VROM resistance training to enhance force throughout the midrange in conjunction with ballistic training to enhance dynamic power may provide an optimal stimulus for increasing athletic performance.

Another potential benefit of VROM resistance training is that these exercises require the athlete to perform countermovements in different phases of the ROM during each set. This would appear to be more sport specific, especially for team sports, because the majority of these sports do not require the athlete to repeatedly perform an identical movement. Therefore, performing training throughout different phases of the ROM under varying loading conditions may help to optimise an athlete's performance by enhancing the true movement specificity of training. However, whether this method of training is superior to full ROM resistance training is unknown, and therefore warrants further investigation.

4.6 CONCLUSION

The results of this study suggest that VROM training provides superior peak force output during a resistance training session when compared with full ROM training. This method of resistance training may be included in an athlete's program to enhance force output throughout the midrange of the movement. However, whether this method of training provides superior performance gains when included into an athlete's training program requires further research.

4.7 IMPLICATIONS ON THE GOAL OF THIS THESIS

Based on the results of Experiment 1, VROM training allows an athlete to lift loads far in excess of what they could lift throughout the full ROM. In addition, significantly higher peak force levels can be produced during the limited ROM sets. These findings provide an answer to Experimental Question 1, by supplying evidence that the exercises performed during a VROM training session have the potential to elicit superior chronic adaptations in comparison with full ROM training.

Whether VROM training provides enhanced benefits in comparison with full ROM resistance training, and if so, what the actual mechanisms behind these adaptations are, is the focus of Experimental Question 2. One of these proposed mechanisms was a change in muscle architecture to enhance force production in the midrange of the movement. As previously mentioned in Section 2.2.4, numerous studies have examined muscle architecture in the lower limb and related this to performance. However, no prior studies have attempted to determine the relationship, if any, between upper body muscle architecture and functioning in a range of multi-joint performance tests. Therefore, Experiment 2 is an examination of the relationship between muscle architecture of the triceps brachii and upper body strength, power and musculotendinous stiffness.

Chapter 4

EXPERIMENT 2:

The Relationship Between Selected Measures of Upper-body Performance and Muscle Architecture

4.1 ABSTRACT

The relationship between upper body performance and muscle architecture has received only limited scientific attention. Therefore, the aim of this study was to examine the relationship between the muscle architecture and performance characteristics of the musculature involved in the upper body pressing movement. Thirty male athletes with extensive strength training backgrounds (age: 23.4 $\pm$ 2.6 yr, height: 180.9 $\pm$ 5.5 cm, mass: 95.2 $\pm$ 13.0 kg, 1RM bench press: 126.8 $\pm$ 10.2 kg) participated in this study. Testing consisted of bench throws both with and without elastic energy contribution, isokinetic bench press and isometric strength tests for upper body performance. Upper body musculotendinous stiffness and ultrasound scans of the medial and long heads of the triceps brachii were assessed to examine muscle architectural properties. Partial correlations, which controlled for each independent variable, revealed that muscle thickness was significantly ($p<0.05$, r = 0.47 - 0.66) correlated with most performance variables. However, neither pennation angle nor corrected angle (pennation angle/muscle thickness) was significantly correlated with any performance variable. Therefore, of the variables assessed muscle thickness was the most highly correlated with upper body pressing potential. This suggests that training programs attempting to increase upper body pressing performance should focus on increasing muscle bulk.

4.2 INTRODUCTION

The ability to produce upper body strength and power is essential in a wide array of sports, especially those where athletes come into contact with one another (Baker, 2001). Previous research has shown that upper body pressing strength is one of the most accurate predictors of an athlete's ability to reach the elite level in body contact sports such as rugby league and American football (Baker, 2001; Black and Roundy, 1994).

While strength and power are important characteristics, another vital athletic attribute in a number of sports is speed of movement (Black and Roundy, 1994). However, the results of a number of previous studies examining muscle architectural properties in the lower limbs suggests that the characteristics that determine strength and speed potential are in opposition to one another (Brechue and Abe, 2002; Kawakami *et al.*, 1993; Kumagai *et al.*, 2000). For example, the architectural features of athletes in sports that rely predominately on dynamic power at high contraction velocities (eg. sprinting), consist of lower angles of pennation and long muscle fascicles (Kumagai *et al.*, 2000). This appears logical because of the advantages in potential shortening velocity provided by these characteristics (Kumagai *et al.*, 2000). In contrast, athletes participating in sports that are more focussed on strength and power at lower contraction velocities (eg. weightlifting), have muscle characteristics that favour higher angles of pennation and a subsequent increase in physiological cross-sectional area (PCSA) (Brechue and Abe, 2002). Once again, this appears plausible due to the advantages in mechanical leverage provided by these characteristics.

While these earlier studies have investigated the architectural features of the lower body muscles in athletes, examination of the these properties in the upper body has received only limited scientific examination. Although previous studies have examined the architectural properties of the arm (Amis, Dowson and Wright, 1979; An, Hui, Morrey, Linscheid and Chai, 1981; Brand, Beach and Thompson, 1981; Lieber, Jacobsen, Fazeli, Abrams and Botte, 1992; Veeger, Van der Helm, Van der Woude, Pronk and Rozendal, 1991; Wood, Meek and Jacobsen, 1989), the effect of training on muscle architecture (Blazevich and Giorgi, 2001; Kanehisa, Nagareda, Kawakami, Akima, Masani, Kouzaki and Fukunaga, 2002) and differences in architecture between the muscles of untrained and resistance trained subjects (Kawakami *et al.*, 1993), only one previous study has examined the relationship between upper body architectural properties and pressing performance (Brechue and Abe, 2002). However, this study only examined the relationship between architecture and maximal strength in powerlifters; a subject group that participates in a sport biased towards maximal strength, low velocity pressing movements. Consequently, the architectural adaptations inherent in their muscle groups would not accurately represent the properties of athletes who participate in sports that require optimal performance throughout all aspects of the force-velocity relationship. This would appear to be the population that would benefit most from research into the relationship between muscle architecture and performance, because of the need to ensure that the relationship between these two factors provides the best all-round performance. Therefore, the purpose of this study was to examine the relationship between the muscle architecture of the long and medial heads of the triceps brachii and upper body pressing performance and musculotendinous stiffness in athletes participating in a sport that requires both high speed and high force muscle contractions.

4.2.1 Statement of the Problem

Despite the potential for muscle architecture to affect power production, no previous studies have examined the relationship between pennation angle or muscle thickness and multiple facets of upper body performance.

4.2.2 Experiment Specific Hypotheses

Based on the findings of the numerous studies performed in the area of muscle architecture and performance in the lower body, it is hypothesised that:

1. Muscle thickness will be more strongly correlated with performance measures biased towards high force production, for example isometric strength, than pennation angle.
2. Pennation angle will be negatively correlated with movements that are biased towards speed of movement, for example ballistic bench throw displacement.
3. Corrected pennation angle will correlate strongly with all performance measures.
4. Both muscle thickness and pennation angle will be significantly correlated with musculotendinous stiffness.

4.2.3 Limitations

1. Muscle architecture of the triceps brachii does not include an assessment of one of the prime movers in the pressing movement, the pectoralis major.
2. Musculotendinous stiffness was calculated using an arbitrary load, and therefore does not provide a measure of maximal stiffness of the system.

3. The subject's training schedule may have resulted in fatigue during the performance tests.
4. No tests were included that relied predominantly on speed of movement.

4.2.4 Delimitations

1. The subject's possessed resistance training experience, and therefore the results of this study are only applicable to a similar population.
2. The muscles tested, the long and medial heads of the triceps brachii, were assumed to represent the architectural properties of the muscles involved in the kinetic chain.

4.3 METHODOLOGY

4.3.1 Subjects

Thirty male, professional rugby league players (age: 23.4 $\pm$ 2.6 yr, height: 180.9 $\pm$ 5.5 cm, mass: 95.2 $\pm$ 13.0 kg, 1RM bench press: 126.8 $\pm$ 10.2 kg) with a minimum of one year of resistance training experience volunteered to participate in the present study. The subjects were all members of the same professional rugby league training squad, and had been participating in 12 weeks of continuous, periodised resistance and plyometric training prior to the study as part of their off- and pre-season training microcycles. This study was approved by the Central Queensland University Human Research Ethics Committee (approval number H05/09-105). All subjects were required to complete both informed consent and pre-activity readiness questionnaire forms prior to any involvement in the study.

4.3.2 Experimental Protocol

The subjects participated in two testing sessions on separate days. An extended methodology and assessment of the reliability of each test is provided in Appendix A. The first session was performed at Central Queensland Medical Imaging, and consisted of ultrasound scans for assessment of the muscle architecture of the long and medial heads of the triceps brachii. The second session was performed in the Health and Human Performance Laboratory at Central Queensland University, and consisted of the performance and neuromuscular activation measures. The subjects did not perform any upper body resistance training in the 48 hours prior to either testing session.

Session One – Muscle Architecture

This session consisted of measurement of the pennation angles and muscle thickness of the long and medial heads of the triceps brachii. Muscle architecture was assessed using B-mode ultrasonography. Scanning was performed using an Acuson Antares Premium Edition (Siemens, U.S.A) scanning at a frequency of 11.4 MHz. Pilot testing revealed that this scanning frequency allowed for the optimal compromise between image clarity, which increases with scanning frequency, and image depth, which has an inverse relationship with scanning frequency (Walker, Cartwright, Wiesler and Caress, 2004).

Although the pectoralis major muscle is a prime mover in the pressing movement, architectural assessment of this muscle would have produced too many sources of error because of its general shape and widespread attachment and insertion points. Therefore, muscle architecture of the long and medial heads of the triceps brachii in the subject's right arm was examined. While these two heads of the triceps brachii are not the only muscles contributing to the pressing movement, due to their role in elbow extension they have been shown previously to be major contributors (Elliott *et al.*, 1989). Furthermore, previous studies examining the relationship between muscle architecture and performance in the lower limb have found that the architectural features of the synergistic muscles involved in complex movements are similar (Abe, Kumagai and Brechue, 1999; Brechue and Abe, 2002). For example, the comparison performed in Section 2.2.4 showed that sprinters possess lower pennation angles and longer muscle fascicles of the quadriceps and gastrocnemius muscles when compared to endurance athletes. Whether this similarity in the relationship between architectural features of different muscles in the upper body is unknown, however, it would appear logical for the muscles involved in the kinetic chain to possess similar architectural properties based on the results observed in the lower body (Abe *et al.*, 1999; Brechue and Abe, 2002). Therefore, the architectural features of these two heads of the triceps brachii would appear to provide evidence of the architectural properties of the muscles involved in the upper body pressing movement.

In order to replicate the bench press movement, the architectural features were examined with the subject in a prone, inverted bench press position. To assume this position, the subjects were instructed to lay face down on a plinth and lightly grip a tripod mounted handle with their right hand. The plinth was then adjusted until the upper arm was parallel to the ground at an elbow flexion angle of 90^{o}. The subjects were required to ensure that their upper arm was relaxed, removing the potential for a change in muscle architecture due to a contraction. This position, along with the measurements performed to locate the scanning site, is displayed in Figure 4.1.

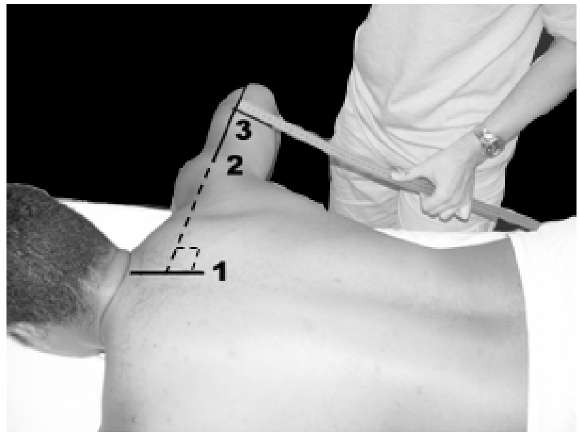

Figure 4.1. Determination of the ultrasound measurement position.
1 Spinal column.
2 Upper arm midline joining the olecranon process and the upper arm midpoint.
3 Forty percent of the distance from the olecranon process to the acromion process marked along the upper arm midline. From this point a perpendicular line was drawn, on which the ultrasound scan was performed.

With the subject lying in this position, a line was drawn along the spinal column by palpating the vertebrae. The distance between the posterior axillary fold and the superior aspect of the shoulder in a line running parallel with the spinal column was then recorded. Two positions were then marked, the first halfway along this line and the second on the olecranon process. Using these marks, an upper arm midline was drawn at a 90^{o} angle to the spinal column, joining the olecranon process and the upper arm midpoint. The acromion process was then palpated and marked, and the distance between this point and the olecranon process was recorded. A mark along the upper arm midline was then made at 40% of the distance from the olecranon process to the acromion process, starting from the olecranon process. A line perpendicular to this point was then drawn from the upper arm midline around the underside of the arm. The transducer scanning position was then determined by slowly tracking the transducer head along this line, while remaining parallel to the upper arm midline, until the thickest region of the triceps was located. Once this position was located the transducer, if necessary, was rotated slightly until the image of the humerus was directly horizontal on the screen. When the scanning position was deemed correct, an ultrasound image was recorded, with an example of this displayed in Figure 4.2.

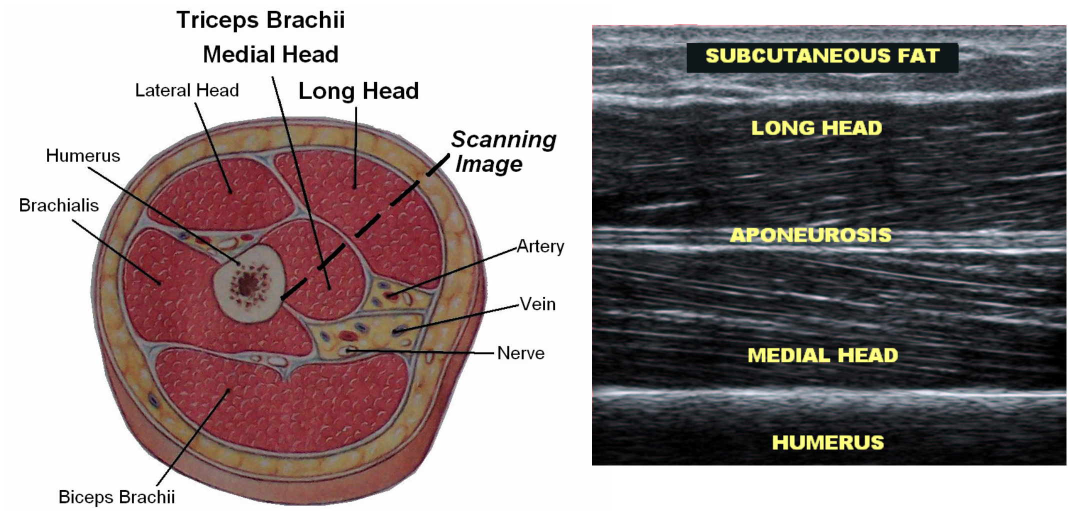

Figure 4.2. Ultrasound scan of the medial and long heads of the triceps brachii, with important architectural features labelled. The image on the left displays the plane of the scan. The image on the right shows the actual image recorded. The image on the left is adapted from Martini, Ober, Garrison, Welch and Hutchings (1998).

The scanning procedure explained above allowed for the same musculature to be examined using a similar testing position to that performed previously by Kawakami *et al.*, (1993). The difference between the two scanning positions was that the present study incorporated an inverted posture, as this position allowed for a replication of the musculoskeletal position during the bench press exercise. This was deemed necessary to compare the architectural properties of the upper arm pressing musculature with the actual performance results. This testing position also allowed for reliable test-retest positioning of the ultrasound transducer, with the results of the reliability study performed by the investigators (See Appendices A) revealing reliable mean test-retest ICC values for the measurements of pennation angle (R = 0.85 $\pm$ 0.07) and muscle thickness (R = 0.94 $\pm$ 0.02).

Values for muscle architecture were derived by determining the pennation angles and muscle thickness of the long and medial heads combined in both the proximal and distal portions of the ultrasound image. Pennation angle was defined as the angle between the muscle fascicle and the tendon aponeurosis. Muscle thickness was deemed the thickness of each muscle at either edge of the image. All measurements were performed using Scion Image analysis software (Scion Corporation, U.S.A) and corrected for the scale used during scanning. An example of these measurements is provided in Figure 4.3.

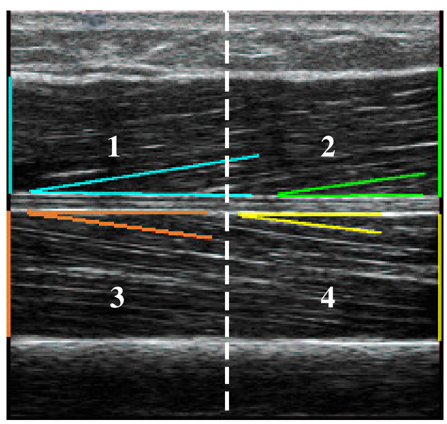

Figure 4.3. An example of muscle thickness and pennation angle measurement of the long and medial heads of the triceps brachii.
The image was split into proximal and distal regions (indicated by the white, dashed vertical line), with the right side of the image representing the proximal edge of the image.
1 Distal long head (blue)
2 Proximal long head (green)
3 Distal medial head (red)
4 Proximal medial head (yellow)

From the results for thickness and pennation angle, a total of three independent variables were produced. These were mean pennation angle, muscle thickness and corrected angle. Mean corrected angle is represented by the mean pennation angle divided by the mean muscle thickness. By performing this correction, a variable was produced that reported the pennation angle per centimetre of muscle thickness. This was performed to create a variable that would overcome the effect of muscle thickness on pennation angle, and was believed to potentially provide a greater insight into the relationship between overall muscle architecture and performance.

Although an assumption for fascicle length is commonly made based on the results for pennation angles and muscle thickness in previous studies (Abe, Fukashiro, Harada and Kawamoto, 2001; Blazevich and Giorgi, 2001; Brechue and Abe, 2002; Kumagai *et al.*, 2000; Muramatsu, Muraoka, Kawakami, Shibayama and Fukunaga, 2002), no such attempt was performed in the present study due to the combination of the non-uniform curvature of the fascicles and the shape of the muscle. The calculation of this variable was thought to have introduced too much potential for measurement error. In addition, the corrected pennation angle measurement provided a measure of pennation angle relative to muscle thickness, which is the relationship that the commonly used fascicle length equation explores.

Session Two - Performance

This session consisted of isokinetic bench press, ballistic bench throws and isometric bench press, with verbal encouragement provided by the investigator during all performance tests. In addition to these measures, upper body MTS was also assessed. All force data for the second testing session was recorded using a force plate

(Advanced Mechanical Technology Inc., U.S.A.) outputting to a Pentium 4 computer. Analogue to digital conversion of the data was performed using a combination of Labview PCI-6034E and PCI-6024E data acquisition cards (National Instruments, U.S.A.), with a custom written Labview software (National Instruments, U.S.A.) program acquiring and analysing data at a sample rate of 1000 Hz. A custom made bench press with no padding was designed and mounted on the force plate to ensure optimal transference of force. This force plate mounted lifting platform is similar to the equipment used in previous studies to assess upper body performance and musculotendinous stiffness (Wilson, Murphy and Pryor, 1994).

In chronological order, the second testing session began with a warm-up, which consisted of five minutes of steady state rowing at 150 Watts on a rowing ergometer (Concept2, U.S.A.). This was followed by tests of upper body MTS, isokinetic bench press, ballistic bench throws and finally isometric bench press.

Test 1 - Upper body MTS

Subjects performed the upper body MTS tests on the force plate mounted lifting bench inside a power cage. The methodology and data analysis was similar to that performed by Wilson *et al.* (1994). Briefly, the subjects were required to lift a load of 60 kg to an elbow joint angle of 100^{o} and statically hold it in this position. A light perturbation was then applied to the barbell. A total of four perturbations were applied, with a 15 second rest between trials. The damped oscillation recorded from the force values allowed for calculation of the upper body MTS value. The median two values of the four tests were used for data analysis.

The one major difference to the previous research is that in this study the subjects only performed the MTS test with an absolute load of 60 kg. A single absolute load was chosen because it was anticipated that performing tests with multiple loads would have resulted in considerable fatigue to the subjects, which may have negatively impacted the remaining functional tests. Therefore, an absolute load of 60 kg, which was approximately 45% of the subject's mean predicted 1RM, was chosen based on pilot studies showing it provided reliable results (R=0.92). This load also replicated the mass that would be used for peak power ballistic bench throw training (Baker, Nance and Moore, 2001), and therefore provided a measure of MTS against an external load which is commonly used during a training session.

The force/time curves were collected via the custom bench mounted force plate (Advanced Mechanical Technology Inc., U.S.A.). Musculotendinous stiffness of the two selected trials was analysed using a custom written Labview (National Instruments, U.S.A.) software package that incorporated the damped spring model calculations provided by McNair, Wood and Marshall (1992). The mathematical steps required to perform this equation are provided in Appendix A.

Test 2 - Isokinetic Bench Press

The subjects performed four sets of five repetitions of concentric lift only isokinetic bench press. Two sets each were performed throughout the full ROM, with the remaining two sets only performed throughout the terminal half of the ROM. These tests were performed using a custom made bench press attachment which was fastened to an isokinetic dynamometer (Biodex System 3, U.S.A.). The dynamometer was used to record position data, which was synchronised with the force plate data and sampled at 1000 Hz. The dynamometer was also used to control the velocity of the movement, which was kept at $45^{o} \cdot sec^{-1}$ to replicate a heavy bench press lift (Lander *et al.*, 1985).

The subjects were instructed to lift the bar with as much force as possible during the tests. Once the bar reached full extension they were then instructed to lightly pull the bar back down to their chest. All five repetitions for each set were performed consecutively, with a one minute rest between sets. Data analysis consisted of peak and mean force values. Furthermore, because of the twin force peaks evident during the full ROM isokinetic bench press, with the first peak occurring during the countermovement, time to second peak force was also examined.

Test 3 - Ballistic Bench Throws

The subjects were required to perform three repetitions each of three different forms of ballistic bench throws. All throws were performed using a Smith Machine (Calgym, Australia) barbell with a 60 kg load, a testing procedure similar to the protocols used as part of their resistance training program. These throws consisted of full ROM countermovement throws, as well as both full and half ROM static-start throws. The subjects performed the countermovement throws by holding the barbell at full elbow extension, then lowering the barbell to the chest and throwing upwards for maximal height.

In contrast, the static-start throws were performed with the bar held stationary at the bottom of the movement using a Plyopower™ braking mechanism (Fitness Technologies, Australia). For the full ROM static-start throws, the bottom of the movement was in the position where the barbell lightly touched the chest. However, for the half ROM static-start throws the bottom position was at the halfway mark of the bench press ROM. This was assessed by measuring the subject's full ROM bench press using a digital position transducer (IDM Instruments, Australia), then locating the midpoint.

Testing consisted of the subjects throwing the barbell for maximum height when instructed by the principle investigator. Performance of both countermovement and static-start throws allowed for assessment of ballistic power potential with and without the contribution of the stretch-shortening cycle, with each repetition separated by a 15 second rest interval. The mean bench throw height, measured using the position transducer, and peak and mean force values, assessed via the force plate, for each of the three tests were recorded and analysed.

Test 4 - Isometric Bench Press

Isometric tests were performed at each quarter of the bench press ROM, including on the chest and at ¾, ½ and ¼ of the ROM from terminal elbow extension. These tests were performed using the Smith Machine (Calgym, Australia), which was modified to include a custom made isometric bench press attachment that restricted vertical movement of the bar beyond the desired testing position. Each position in the ROM was determined by measuring the full ROM bar displacement for each subject using the position transducer. This value was then divided into quarters and one test was performed in each position. A five second ramp protocol was performed for the isometric tests to prevent shoulder injury, with a two second ramp followed by the final three seconds of the test performed at maximal voluntary contraction. A one minute rest was allocated between trials. Due to the ramp protocol removing the potential for assessment of rate of force development and force decay, data analysis focussed on the peak force value at each position.

4.3.3 Statistical Analysis

Partial correlation co-efficient analysis was performed, with a control included for the results of the other variable in the case of mean pennation angle and mean muscle thickness. This allowed for the relationship of each variable (for example, pennation angle) to the performance test to be examined whilst fixing the influence of the other variable (for example, muscle thickness). Pearson product moment correlations were performed for the mean corrected angle, without control for either of the other two variables, as the nature of the correction already included a control for each variable. Prior to the performance of this analysis, the normality, linearity and homoscedasticity of the data was assessed to ensure that no violations of these assumptions had occurred.

Significant correlation co-efficient values (r) of between 0.50 and 0.70 were deemed to be low strength, 0.71 and 0.80 moderate strength, 0.81 and 0.90 high strength and >0.90 very high strength (Vincent, 1995). Due to a combination of these thresholds, and the degrees of freedom involved in the analysis, the alpha level was set at $p<0.01$.

4.4 RESULTS

The descriptive results for each test are provided in Table 4.1, along with the standard error of the measurement (SEM). The results for each correlation are provided in Table 4.2. The results showed that mean muscle thickness was significantly correlated (*p*<0.05, r = 0.47 - 0.66) with all performance measures, except half ROM static bench throw displacement and MTS. In contrast, neither mean pennation angle nor mean corrected angle were significantly correlated with any performance measure.

Table 4.1. Mean (± SD) results for each test.
The results for the SEM of each test, performed prior to this study, are provided.

TEST	MEAN RESULTS
Countermovement bench throw (cm) (SEM=0.9)	13.0 ± 4.2
Static bench throw (cm) (SEM=1.4)	12.5 ± 4.2
Half ROM static throw (cm) (SEM=1.1)	12.7 ± 4.3
Isokinetic time to 2nd force peak (ms) (SEM=11)	741 ± 74
Isokinetic peak force (N) (SEM=78)	1338 ± 279
Half ROM isokinetic peak force (N) (SEM=84)	1391 ± 348
Isometric chest peak force (N) (SEM=79)	1289 ± 393
Isometric 3/4 ROM peak force (N) (SEM=60)	1383 ± 288
Isometric 1/2 peak force (N) (SEM=109)	1674 ± 213
Isometric 1/4 peak force (N) (SEM=197)	1884 ± 200
Musculotendinous stiffness ($N \cdot m^{-1}$) (SEM=2393)	18586 ± 8723
Mean pennation angle (^{o}) (SEM=0.8)	9.3 ± 2.0
Mean muscle thickness (cm) (SEM=0.1)	1.2 ± 0.3
Mean corrected angle ($^{o} \cdot cm^{-1}$) (SEM=1.4)	9.4 ± 3.5

Table 4.2. The correlation between muscle architectural properties and performance in each of the physical tests.
Represented by partial r values for mean pennation angle and muscle thickness.

TEST	MEAN PENNATION ANGLE	MEAN MUSCLE THICKNESS	MEAN CORRECTED ANGLE
Countermovement bench throw	0.10	0.50*	-0.29
Static bench throw	0.18	0.53*	-0.26
Half ROM static throw	0.07	0.22	-0.28
Isokinetic time to 2nd force peak	0.40	-0.53*	-0.26
Isokinetic peak force	0.33	0.66*	-0.05
Half ROM isokinetic peak force	-0.18	0.58*	-0.07
Isometric chest peak force	-0.12	0.65*	-0.32
Isometric 3/4 ROM peak force	-0.24	0.65*	-0.42
Isometric 1/2 peak force	-0.21	0.66*	-0.42
Isometric 1/4 peak force	-0.22	0.47*	-0.08
Musculotendinous stiffness	-0.14	0.15	0.06

* indicates a significant correlation ($p<0.05$)

5.5 DISCUSSION

The results of this study suggest that the relationship between upper body pressing performance, even during explosive power movements, and pennation angle of the elbow extensors is limited. Examination of numerous upper body strength, power and time to peak force measures revealed that muscle thickness was more closely related to performance than pennation angle. This finding supports the results of a previous study performed by Brechue and Abe (2002), and the proposed outcomes suggested in Hypothesis 1. Although it is logical that thicker muscles would produce higher force levels, the relationship between pennation angle of the triceps brachii and upper body pressing performance is somewhat obscure. Based on the leverage principles outlined by Kumagai *et al.*, (2000), lower angles of pennation would appear to be beneficial for dynamic movements such as the ballistic bench throws. However, this was not supported by the findings of the present study, and refuted Hypothesis 2. Furthermore, even when pennation angle was divided by muscle thickness to create a mean corrected angle, there were still only weak correlations with all performance measures. This contradicts the proposed outcome of Hypothesis 3. These results suggest that in a multi-joint movement, the relationship between pennation angle and performance is limited. This supports the findings of previous anatomical modelling and animal-based dissection research (Nagano and Gerritsen, 2001; Powell, Roy, Kanim, Bello and Edgerton, 1984), but is in contrast to the findings of correlational research performed by Brechue and Abe (2002) and the hypothesis suggested by Kumagai *et al.*, (2000). While the study by Brechue and Abe (2002) found a significant, albeit weak, negative relationship between pennation angle relative to fat free mass and bench press performance, no significant correlations were found in the present study between mean corrected angle and any of the measures in the present study. In an effort by the researchers to clarify this discrepancy, the data for both pennation angle and muscle thickness were analysed using separate Pearsons product moment correlation coefficient equations without between-variable controls *ex post facto*. This analysis also resulted in no significant ($p<0.05$) correlations between pennation angle and performance.

A potential explanation for this finding is the role of the pennation angle in transfer of force along the kinetic chain. It is well established that the effect of pennation angles on tension production is a function of the cosine of the pennation angle (Powell *et al.*, 1984; Sacks and Roy, 1982). Therefore, the mechanical efficiency of the fascicle is reduced as the pennation angle increases. However, the degree of difference is only relatively small in comparison to architectural properties such as fascicle length (Sacks and Roy, 1982). While the effect on mechanical efficiency appears limited, an increase in pennation angle may be related to an augmentation in the amount of contractile tissue attached to the tendon, resulting in a subsequent increase in PCSA.

This relationship can be explained by the creation of an idealized model of muscle-tendon architecture. Despite the numerous limitations inherent in this type of model (see Appendix B), such as the exclusion of variables including elastic energy contribution, interdigitation of fibres, tapering of the fascicles and non-uniform lengthening of the muscle fibres (Chanaud, Pratt and Loeb, 1991; Loeb, Pratt, Chanaud and Richmond, 1987; Pappas, Asakawa, Delp, Zajac and Drace, 2002), it does provide an insight into the role of muscle architecture on performance. Although the present study examined the long and medial heads of the triceps brachii, the shape of this muscle group presents a number of confounding variables in the production of an idealised muscle-tendon model. Therefore, a simple bipennate model based on the images produced during this study was created. This model consists of the medial and long heads of the triceps forming a three dimensional cylinder, with the surface area around the diameter of the cylinder representing the origin aponeurosis and the insertion aponeurosis longitudinal and centred with the cylinder. This musculotendinous unit, with a joint position similar to the biceps brachii at an elbow flexion angle of 90^{o}, is provided in Figure 4.4.

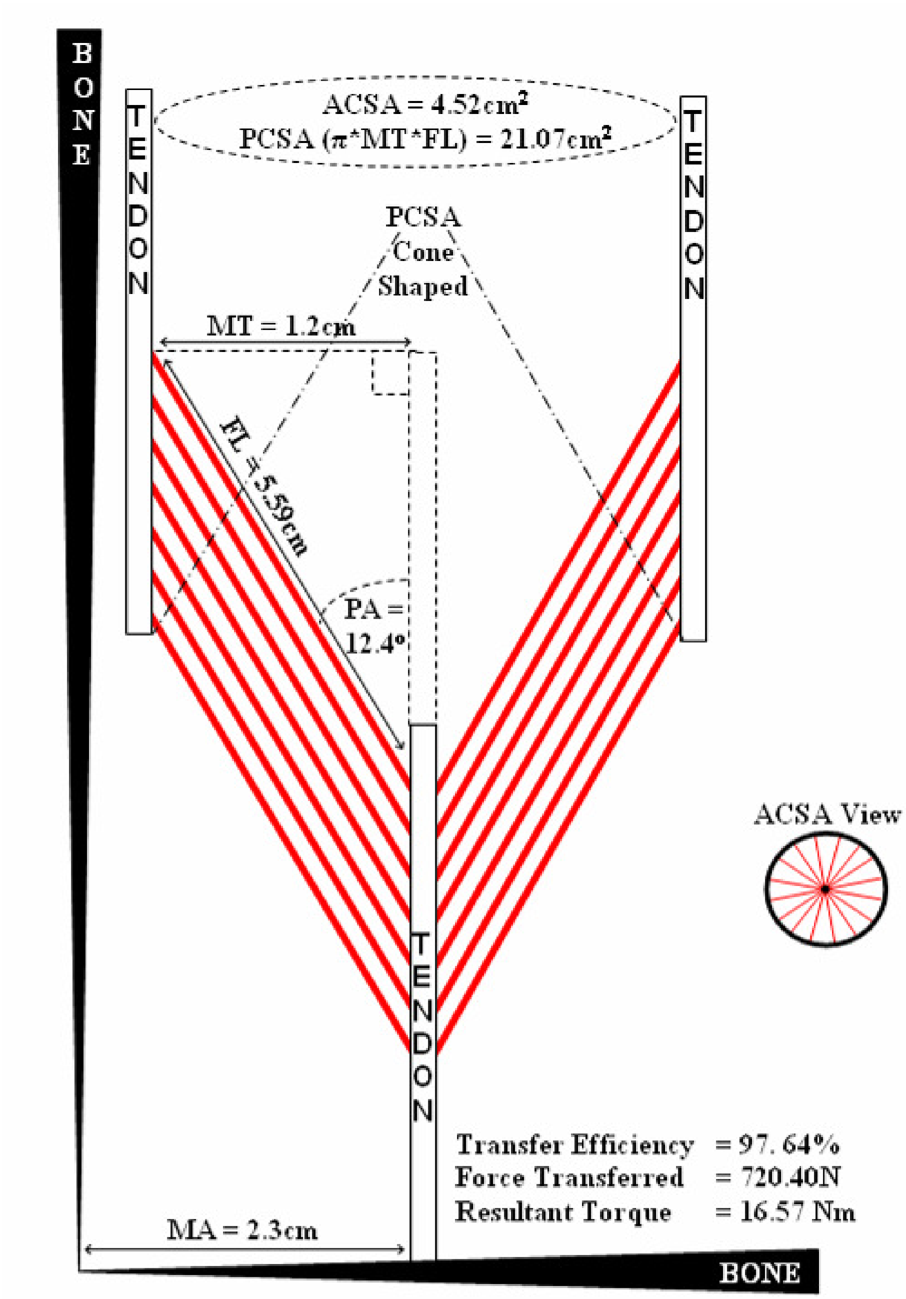

Figure 4.4. Idealized bipennate model of muscle architecture.
The outcome measure for this model is torque about the joint axis of rotation. In this model PCSA = π*MT*FL, because the bipennate nature of the model results in the three dimensional magnitude of muscle area running perpendicular to the longitudinal axis of the muscle fascicles forming a conal shape. The independent variables consisting of pennation angle and muscle thickness are derived from the findings of this study, while the moment arm value and force per cm^2 of PCSA are derived from the results of Murray (1997) and Kawakami *et al.* (1994) respectively.

Based on the architectural properties provided in Figure 4.4, it is possible to determine the contribution of different variables to rotational torque about the axis of rotation of the joint using trigonometry. The limited relationship between pennation angle and performance is evident when changes in this variable are applied to the model, and the resultant torque generation is observed. The results of a $\pm$10% change in the independent variables of pennation angle and muscle thickness are provided in Table 4.3.

Table 4.3. A comparison of the effect of a $\pm$10% change in pennation angle or muscle thickness on rotational torque about the joint axis, with the assumption of total muscle volume remaining relative to PCSA.

A) Change in pennation angle (PA), with adaptations in the fascicle length corresponding to changes in PA accounted for in the calculation of force production. This removes the confounding effect of a change in muscle thickness (MT).

B) Change in MT, with adaptations in the fascicle length corresponding to changes in MT accounted for in the calculation of force production. This removes the confounding effect of a change in PA.

C) Changes in PA and MT, providing an example of the somewhat negated impact these variables produce when occurring in unison.

VARIABLE NAME	VARIABLE VALUES	PCSA (cm^2)	TOR-QUE (N·m)	MECHANICAL EFFICIENCY (%)	CHANGE (%)
A) Δ PA (^{o}) (includes Δ FL to maintain muscle thickness)					
Mean (PA, FL)	12.4^o, 5.59cm	21.07	16.57	97.64	NA
+ 10%	13.6^o, 5.10cm	19.23	13.73	97.26	-17.1
- 10%	11.2^o, 6.18cm	23.30	20.33	98.07	22.7
B) Δ MT (cm) (includes Δ FL to maintain PA)					
Mean (MT, FL)	1.20, 5.59cm	21.07	16.57	97.64	NA
+ 10%	1.32, 6.15cm	25.50	22.05	97.64	+ 33.1
- 10%	1.08, 5.03cm	17.07	12.07	97.64	- 27.2
C) Δ PA + subsequent Δ MT – no effect on FL					
Mean (PA, MT)	12.4^o, 1.20cm	21.07	16.57	97.64	NA
+ 10%	13.6^o, 1.31cm	23.01	18.01	97.26	+ 8.7
- 10%	11.2^o, 1.09cm	19.14	15.11	98.07	- 8.8

The results in Table 4.3 outline that a 10% increase or decrease in pennation angle with no effect on muscle thickness, which represents the analysis of pennation angle with muscle thickness as a control variable performed in this study, results in a -17.1% and +22.7% change in torque respectively. While this is a noticeable difference, its magnitude is diminished when compared to the +33.1% and -27.2% respective difference in torque which results in response to an alteration in muscle thickness of an identical magnitude, which represents the analysis of muscle thickness with pennation angle as a control variable performed in the present study. In fact, the above calculations revealed that the majority of the change in torque production in response to a modification in pennation angle was actually due to the variation in fascicle length, and subsequent alteration to PCSA, which was necessary to maintain muscle thickness. This variation in fascicle length resulted in a subsequent change in the contractile force of the fascicle, with the alteration in mechanical efficiency due to the change in pennation angle being of only a very small magnitude (+10% change in pennation angle = -1.1% change in mechanical efficiency, -10% change in pennation angle = +0.8% change in mechanical efficiency). In regards to the limited relationship between corrected angle and performance, it would appear that the thickness of the muscle is the predominant factor, consequently restricting the application of a test for corrected pennation angle to determine performance.

The results of this model support the primary finding of the present study; that muscle thickness of the long and medial heads of the triceps brachii was significantly correlated with nearly all of the performance tests. As predicted, muscle thickness was a major contributor to force production and bench throw height. However, the negative relationship with isokinetic time to 2nd peak force was not expected. This finding suggests that time to 2nd peak force decreases with increased thickness of the muscle, with a potential explanation for this finding related to the subject's resistance training experience. Those subjects with thicker muscles are likely to have greater adaptations in their force/ROM strength curve as a result of their training history. These adaptations are likely to be biased towards producing peak force towards the start of the movement, because this is where maximal force is required to overcome the 'sticking region' of the exercise and successfully perform the lift (Lander *et al.*, 1985). Therefore, those athletes with extensive resistance training backgrounds are more likely to produce their second force peak towards the start of the concentric phase of the lift.

While muscle thickness was correlated with most of the performance measures in the present study, the strength of this correlation was at most moderate. Other contributing factors to these performance tests may have been co-ordination and neuromuscular activation, which were not assessed but would also affect functional performance in these tasks.

In addition, none of the independent variables were significantly correlated with MTS, which contradicted Hypothesis 4. Although a thicker muscle would theoretically be stiffer due to an increase in cross-bridge and potentially connective tissue size, this was not found in the present study. Furthermore, although changes in leverage are evident as a result of differences in pennation angle, this variable was also not related to MTS. Although the findings of this study suggest only a very weak relationship between either pennation angle or muscle thickness and MTS, it must be stressed that the movement performed was a complex multi-joint task. The relationship between these architectural properties and MTS during isolated contractions may be different. In addition, although the relationship between pennation angle and the tests performed during this study was almost non-existent, there may have been a number of limiting factors. As previously mentioned, the prime mover of this exercise, the pectoralis major, was excluded because of the difficulty of performing an examination of its architectural properties. Although it is highly likely that this muscle would display similar architectural features to the other synergistic muscles involved in the bench press movement, due to the subject's extensive bench press training history and high levels of strength in the exercise, this hypothesis has not been examined. Furthermore, none of the performance tests examined in the present study were biased towards the speed component of the power spectrum. However, based on the leverage principles of pennation angle, a low angle of pennation would become increasingly beneficial as the speed of contraction increased. Therefore, by neglecting to include a test of speed into the methodology, one of the major benefits that angle of pennation may provide was not examined. Although this may be a limitation of the present study, the ballistic bench throws were performed at a load that allowed for explosive movements to be performed at relatively high velocities. While these tests may have included a considerable speed component, future research should examine the relationship between muscle architecture and movements that rely almost exclusively on speed.

4.6 CONCLUSION

Muscle thickness of the long head of the triceps brachii is correlated with upper body pressing strength and power, while angle of pennation did not demonstrate a strong association with any of the performance tests incorporated in this study.

Therefore, training programs attempting to increase upper body pressing strength and power should focus on increasing muscle bulk.

4.7 IMPLICATIONS ON THE GOAL OF THIS THESIS

Whether VROM training provides enhanced benefits in comparison with full ROM resistance training, and if so, what the actual mechanisms behind these adaptations are, is the focus of Experimental Question 2. One of these proposed mechanisms was a change in muscle architecture to enhance force production in the midrange of the movement. The results of Experiment 2 suggest that an examination of adaptations in pennation angle in response to the proposed training intervention may not provide a mechanistic answer for any adaptations that may occur. However, assessment of muscle architecture would still provide an *in vivo* assessment of muscle thickness, and therefore may provide an insight into alterations in performance attributed to the proposed training program.

The final study, Experiment 3, is a comparison of the effects of a 5-week VROM or full ROM training intervention on upper body performance in professional athletes. This study is the primary focus of this thesis, and attempts to provide the answers to Experimental Question 2.

Chapter 5

EXPERIMENT 3:

The Effects of Variable ROM Training on Performance, Neural Activation, Musculotendinous Stiffness and Muscle Architecture

5.1 ABSTRACT

Variable ROM (VROM) training, which consists of partial ROM training with countermovements performed in a different phase of the ROM for each set, may overcome some of the limitations of traditional full ROM resistance training. This study examined the effect of VROM training on upper body ballistic force production, musculotendinous stiffness, neuromuscular activation and muscle architecture. Twenty-two professional rugby league players (age: 23.7 ± 2.4 yr, height: 180.7 ± 6.5 cm, mass: 96.2 ± 14.5 kg, pre-intervention 6RM bench press: 107.7 ± 18.1 kg) with extensive resistance training backgrounds were assigned to either a VROM or full ROM (CON) strength training group based on their prior bench press strength levels and performance gains. The intervention consisted of a five week, concentric work-matched training program performed in the subject's pre-season. Testing consisted of isokinetic bench press through both full and half ROM from full elbow extension, isometric strength and EMG at one quarter intervals throughout the bench press ROM, bench throws performed both with and without countermovements, upper body musculotendinous stiffness and pennation angles and muscle thickness of long and medial heads of the triceps brachii using ultrasound. Statistical analysis consisted of repeated measures ANOVAs with an alpha level set at p=0.05. The results showed that the VROM intervention significantly increased bench throw displacement both with

(15.5% increase, p=0.002) and without countermovements (15.2% increase, p=0.012), and isokinetic full ROM peak force (10.5% increase, p=0.032). In contrast, no significant performance gains were found in the CON group. These results suggest that VROM training is superior to traditional full ROM resistance training for enhancing power and force in well trained athletes, and should therefore be included in their resistance training program.

5.2 INTRODUCTION

Although traditional full ROM resistance training is a proven method of enhancing strength and power, the results of Experiment 1 in conjunction with the numerous limitations previously cited in the Review of Literature suggest that VROM training may be more efficient for enhancing an athlete's performance. The results of Experiment 1 revealed that peak force increases when a combination of reduced ROM and increased load is performed during bench press training. Not only does this increase the peak force of the exercise, it also results in the peak forces for each set occurring at different phases of the ROM. This may potentially enhance athletic performance by optimising force production throughout the entire ROM. Furthermore, this method of training may also augment the true movement specificity of the exercise in regards to the biomechanical actions that occur during the majority of sports. However, whether these previously mentioned benefits actually occur is unknown.

Previous studies have only examined partial ROM training in one limited ROM, and these studies are both sparse and inconclusive (Graves *et al.*, 1989; Graves *et al.*, 1992; Massey *et al.*, 2005; Massey *et al.*, 2004). Although there is potential for

VROM training to provide numerous benefits for athletes, no previous studies have examined the effect of performing near maximal training with countermovements performed at different joint angles, as proposed in the VROM training method. Due to the athletic and normal daily functioning specificity of this method of resistance training, along with the potential for enhanced athletic performance, it is therefore important to examine the effect of VROM resistance training on functional performance and the architectural properties of the musculotendinous system.

5.2.1 Statement of the Problem

VROM training may provide superior longitudinal performance gains when compared to full ROM training in high level athletes, however this has not been empirically examined.

5.2.2 Experiment Specific Hypotheses

Based on the results of Experiment 1, and the potential benefits of VROM training highlighted in the Review of Literature, it is hypothesised that VROM training will produce significantly superior results for:

1. Ballistic bench throw displacement, due to greater ROM specificity of the training method.
2. Isokinetic peak force, due to an increase in peak force in the terminal phase of the movement.
3. Isometric strength in the terminal phase of the movement, due to enhanced training specificity

In addition, it is also hypothesised that:

4. There will be no significant change in resting pennation angle without a corresponding change in muscle thickness, as the results of Experiment 2 suggest that this architectural feature is not influential enough on its own to result in major performance gains.
5. If Hypothesis 3 is correct, EMG amplitude, expressed for the ¼ ROM isometric test as a percentage of the amplitude of the test performed with the barbell at the chest, will significantly increase in response to the ROM specificity of VROM training.

5.2.3 Limitations

1. The training study was only five weeks in duration to coincide with the subject's training microcycle, which may not have provided enough time for significant architectural adaptations to occur.
2. The subject's training schedule may have resulted in fatigue during the performance tests.
3. Due to the duty of care of the principle investigator, no test of eccentric pressing strength was included in the testing battery (An explanation of the attempts to include an eccentric test, and the rational for its exclusion, are provided in Appendix A).
4. The subject's diet and external training load was not monitored.

5.2.4 Delimitations

1. The subjects possessed extensive resistance training experience, therefore the results of this study are only applicable to a similar population.

5.3 METHODOLOGY

5.3.1 Subjects

Twenty-two male, professional rugby league players (age: 23.7 ± 2.4 yr, height: 180.7 ± 6.5 cm, mass: 96.2 ± 14.5 kg) with a minimum of one year of continuous resistance training experience volunteered to participate in the present study, which was approved by the Central Queensland University Human Research Ethics Committee (approval number H05/09-105). This number of subjects allowed for a high level of statistical power (mean P>0.80, based on the power equations performed in Appendix C).

5.3.2 Experimental Protocol

The subjects in this study were split into two concentric work-matched training groups, based on the results of Experiment 1. The participants were members of the same training squad, and had been participating in 12 weeks of continuous, periodised resistance and plyometric training prior to the study as part of their off-season training macrocycle. This 12 week program was split into two successive six week microcycles, and was prescribed by the primary investigator (see Appendix D). The subject's 6RM bench press strength was tested before, midway and after the 12 week training program prior to the commencement of the experimental training intervention. These tests were performed to allow for division of the subjects into two strength-matched training groups, with similar performance gains in their previous six week cycle being the determinant variable. Matching the subjects for 6RM bench press strength prevented pre-intervention strength imbalances between groups. Furthermore, tracking the subject's strength gains in the microcycles immediately prior to the training intervention reduced the possibility of having uneven performance enhancement potential in the groups prior to commencement of this study.

The training groups were matched for these two factors by ranking each subject based on these variables. The subject groups were then manipulated until the two potential combinations with the most similar strength and performance enhancement potential were determined. The 6RM strength results for each group during tests in weeks one, six and twelve are provided in Figure 5.1. The relative strength gains during the two microcycles leading up to the intervention are provided in Figure 5.2. In addition to providing groups homogenous in strength and performance enhancement potential, the division of subjects also created groups with similar descriptive statistics, which are provided in Table 5.1. Preliminary statistical analysis of the 6RM strength and strength gain data, consisting of a repeated measures ANOVA (2 groups x 3 testing session) for each variable performed at $p<0.05$, revealed no significant pre-intervention 6RM strength or strength gain differences between groups or testing sessions. Although previous studies have shown significant bench press strength gains after shorter duration interventions (Kraemer *et al.*, 2002), the subject's extensive training history resulted in only small, non-significant differences in strength levels. However, for the strength gain data a main effect trend ($F=3.99$, $p=0.060$) was observed for testing session, with strength gains between weeks six to twelve less than during weeks one to six. This would be expected due to the subjects return to training from an off-season rest period, hence the relatively large increase in strength in the first six weeks despite the subject's extensive training history (Kraemer *et al.*, 2002). Basic extrapolation of these results to predict the expected strength increase over the course of the training intervention, if a typical full ROM training program was incorporated, was performed using logarithmic regression. This resulted in an expected strength increase of less than 1.9%. Independent-samples t-tests, performed at $p<0.05$, revealed no significant differences between subject groups for any of their descriptive statistics.

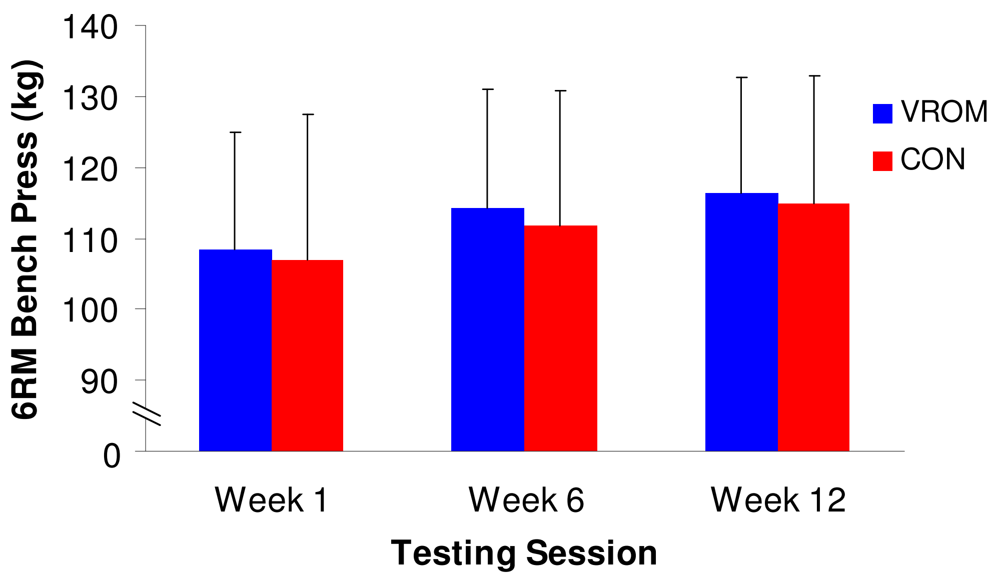

Figure 5.1. Mean bench press strength (±SD) in the 12 weeks prior to the training intervention.

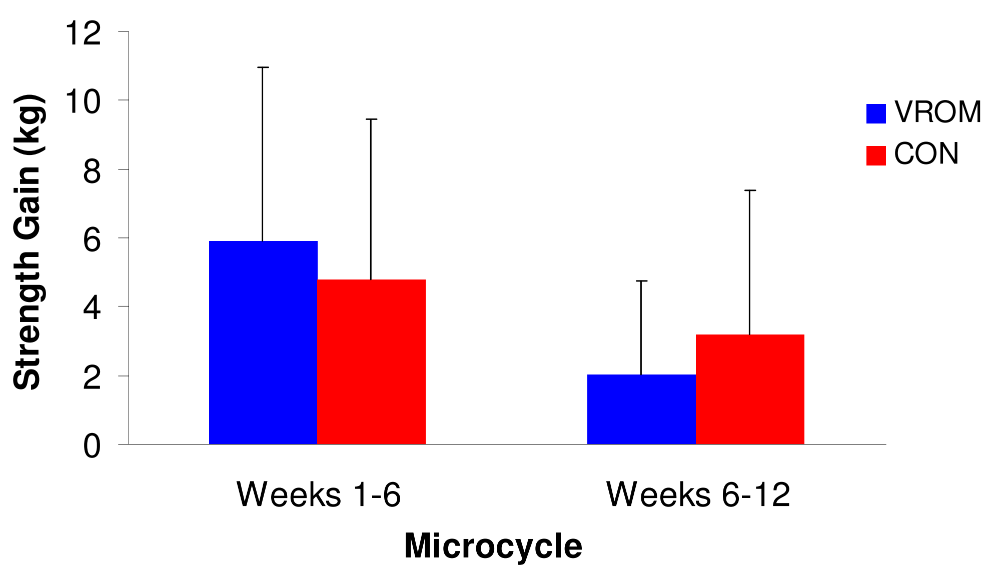

Figure 5.2. Mean strength gains (±SD) from weeks one to six and weeks six to twelve respectively.

Table 5.1. Descriptive statistics of the two subject groups (±SD).

SUBJECT GROUP	AGE (yr)	HEIGHT (cm)	BODY MASS (kg)
VROM	23.6 ± 3.1	180.9 ± 6.9	96.3 ± 12.0
CON	21.7 ± 2.5	180.5 ± 6.3	92.8 ± 12.7

The training programs for both the control (CON) and VROM groups during the intervention are provided in Appendix D, and every session was supervised by the principal investigator. The CON group performed four sets of traditional full ROM bench press, plus a subject determined full ROM warm-up set. In contrast, the VROM group performed two full ROM sets and one set each of three quarter (¾), one half (½) and one quarter (¼) ROM bench press. This resulted in the subjects performing five total sets, one each of full, ¾, ½, ¼ and full ROM in that order, plus a subject determined full ROM warm-up set. This order was reversed for the second training day each week to ensure that the same VROM sets were not performed under fatigue each session.

The extra set for the VROM group allowed for the concentric workload between the two groups to be matched, based on the results of Experiment 1. Both training groups performed two sessions per week, with the bench press exercise performed during each session. This resulted in both groups performing not only the same concentric workload per week upon commencement of the intervention, but additionally the workload increase from the prior training program was identical. This was essential to ensure that both training groups had an equal opportunity to improve performance during the intervention.

The periodisation strategy for the training microcycle was a split wave format, consisting of heavy and light loading sessions, with the number of repetitions performed for the bench press exercise varying between four and twelve repetitions. Although a lower number of repetitions may be considered optimal for increasing strength (Kraemer *et al.*, 2002), it was deemed necessary to establish four repetitions as the lowest number of repetitions performed due to the intense nature of the VROM training program. The repetitions for the bench press section of the training program for the CON and VROM groups are provided in Table 5.2.

Table 5.2 Number of repetitions performed per set by each group during their training session.

SESSION	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5
Heavy	6	4	4	6	8
Light	10	10	12	12	12

The resistance training intervention was performed in conjunction with the teams' skill and fitness drills. While this concurrent training presented a confounding variable in the study, it did provide an ecologically sound examination of the benefits of VROM training in an athletic population. For a detailed example of the entire training program both during and in the lead up to this microcycle, please refer to Appendix D. Subject compliance, assessed by recording subject details every training session, was 100%. If a subject was unable to attend a prescribed session they performed a catch-up session supervised by the investigator.

This experiment limited the VROM training intervention to the upper body pressing movement, with all other components of the training programs remaining identical between groups. This delimitation was performed for a number of reasons.

Firstly, the large volume of lower body exercise performed during the subject's off-season increased the risk of confounding variables affecting the results of the study. Secondly, tracking of strength gains in the previous season, with similar subjects, revealed limited bench press strength enhancement in comparison to other exercises such as the squat and deadlift. This suggests that the subjects possessed an advanced bench press training history in comparison with the other exercises, which is supported by the subject's comparable bench press strength levels to those of elite level athletes participating in similar sports (Baker and Nance, 1999; Mayhew, Ware, Bemben, Wilt, Ward, Farris, Juraszek and Slovak, 1999). Therefore, this reduced the potential for dramatic strength gains regardless of the intervention, which is often seen in training interventions using subjects with limited training experience. In addition, limiting the intervention to a single exercise reduced the potential for extra supervision given to one group affecting the results, as previous research has shown (Coutts, Murphy and Dascombe, 2004). This allowed for minimal extra guidance to be given to the VROM group, therefore removing the potential for this variable to have a confounding effect.

The subjects participated in a total of four testing sessions on separate days, with two sessions each both pre- and post-intervention. The first session was performed at Central Queensland Medical Imaging, and consisted of ultrasound scans for assessment of muscle architecture. The second session was performed in the Health and Human Performance Laboratory at Central Queensland University, and consisted of the performance and neuromuscular activation measures. The subjects did not perform any upper body resistance training in the 48 hours prior to either session. These two testing sessions were then repeated between two and five days after the final training session in the intervention.

The methodology for this study is identical to the protocols performed in Experiment 2, with the exception of the addition of EMG to the testing procedure. Therefore, the protocol for each test will be only briefly described, with an extended methodology provided in Appendix A.

Session One – Muscle Architecture

This session consisted of measurement of the pennation angles and muscle thickness of the long and medial heads of the triceps brachii, assessed using B-mode ultrasonography. Examination of these features was performed in both the proximal and distal portions of the ultrasound image. The results for each of these measures were average to provide mean values for pennation angle and muscle thickness. From these two results, measurements of mean pennation angle, muscle thickness and corrected angle were derived.

Session Two - Performance and Neuromuscular Activation

This session consisted of isokinetic bench press, ballistic bench throws and isometric bench press. In addition to these performance measures, upper body musculotendinous stiffness (MTS) and EMG were also assessed. All force data for the second testing session was recorded using a force plate (Advanced Mechanical Technology Inc., U.S.A.) outputting to a Pentium 4 computer, with a custom written Labview software (National Instruments, U.S.A.) program acquiring data at a sample rate of 1000Hz. A custom made bench press with no padding was designed and mounted on the force plate to ensure optimal transference of force.

<u>Upper body MTS</u>

Following a steady state rowing warm-up performed at 150 Watts on a rowing ergometer (Concept2, U.S.A.), the subjects performed a test of upper body MTS. The subjects performed the upper body MTS tests on the force plate mounted lifting bench inside a power cage. The methodology and data analysis was similar to that performed by Wilson *et al.*, (1994). Briefly, the subjects were required to lift a load of 60 kg to an elbow joint angle of 120^o, where a light perturbation was applied to the barbell. A total of four perturbations were applied, with a 15 second rest between trials. The damped oscillation recorded from the force values allowed for calculation of the upper body MTS value using the equations of McNair *et al.* (1992), which are provided in Appendices A. The median two values of the four tests were used for data analysis.

<u>Isokinetic Bench Press</u>

The subjects performed four sets of five repetitions of concentric only isokinetic bench press. Two sets each were performed throughout the full ROM, with the remaining two sets only performed throughout the terminal half of the ROM. These tests were performed using a custom made bench press attachment which was fastened to an isokinetic dynamometer (Biodex System 3, U.S.A). The dynamometer was used to record position data, which was synchronised with the force plate data and sampled at 1000Hz using a custom written Labview software program (National Instruments, U.S.A.) running on a Pentium 4 computer. The dynamometer was also used to control the velocity of the movement, which was kept at $45^{o}\cdot sec^{-1}$ to replicate a heavy bench press lift (Lander *et al.*, 1985).

The subjects were instructed to lift the bar with as much force as possible during the tests. Once the bar reached full elbow extension, they were then required to lightly pull the bar back down to their chest. All five repetitions for each set were performed consecutively, with a one minute rest between sets.

Data analysis consisted of the assessment of the mean peak force values during the three repetitions in each testing set with the highest peak force values. In addition, the data for the full ROM isokinetic tests was also split into quarters based on ROM. This resulted in a peak force value for each quarter of the ROM, with the sections labelled first quarter (from the chest to one quarter of the ROM), second quarter (from one quarter to half ROM), third quarter (from half to three quarter ROM) and fourth quarter (from three quarter to terminal ROM). The data for the first quarter of the ROM was discarded due to inconsistent results between trials, potentially a result of impact spikes and/or acceleration of the bar prior to reaching constant velocity. Furthermore, because of the twin force peaks evident during isokinetic bench press, with the time to peak force occurring almost instantaneously with the countermovement, time to second peak force was also examined during the full ROM tests.

<u>Bench Throws</u>

The subjects were required to perform three repetitions each of three different forms of ballistic bench throws. All throws were performed using a Smith Machine (Calgym, Australia) barbell loaded with 60 kg. These throws consisted of full ROM countermovement throws, as well as both full and half ROM static-start throws. The subjects performed the countermovement throws by holding the barbell at full elbow extension, then lowering the barbell to the chest and throwing upwards for maximal height.

In contrast, the static-start throws were performed with the barbell held stationary at the bottom of the movement using a Plyopower™ braking mechanism (Fitness Technologies, Australia). This braking mechanism prevented the descent of the barbell towards the subject's chest, effectively resulting in no eccentric loading. By eliminating the eccentric component of the lift, the elastic energy produced by holding the barbell stationary was removed. This resulted in a purely concentric throw, with minimal stretch-shortening cycle contribution. For the full ROM static-start throws, the bottom of the movement was in the position where the barbell lightly touched the chest. However, for the half ROM static-start throws the bottom position was at the halfway mark of the bench press ROM. This was assessed by measuring the subject's full ROM bench press using a position transducer (IDM Instruments, Australia), then locating the midpoint.

Testing consisted of the subjects throwing the barbell for maximum height when instructed by the investigator, with each repetition separated by a 15 second rest interval. The mean bench throw height, measured using the position transducer for each of the three tests was recorded and analysed.

<u>Isometric Bench Press and EMG</u>

Isometric tests were performed with the barbell at the chest and at ¾, ½ and ¼ of the ROM from terminal elbow extension. These tests were performed using the Smith Machine (Calgym, Australia), which was modified to include a custom made isometric bench press attachment that restricted vertical movement of the barbell beyond the desired testing position. A five second ramp protocol was performed for the isometric tests to prevent shoulder injury, with the final three seconds of the test performed at maximal voluntary contraction. A one minute rest interval was allocated between trials to reduce the effect of fatigue on the subsequent trials. Due to the ramp protocol removing the potential for assessment of rate of force development and force decay, data analysis focussed on the peak force value at each position.

During the isometric tests performed at the chest and ¼ ROM positions, EMG of the long head of the triceps brachii and the pectoralis major muscles was performed. Neuromuscular activation was detected using 99.9% silver pre-amplified surface electrodes (Delsys, U.S.A). These electrodes were bipolar, with a single differential, parallel bar electrode configuration consisting of an inter-electrode distance of 10 mm. The electrode placement site for the long head of the triceps brachii was identical to the position of the ultrasound scan. This was chosen because it represented the belly of the muscle. For the pectoralis major, the electrode placement site was located directly superior to the nipple and directed along a line halfway between the most superior aspect of the axillary fold and the attachment of the xiphoid process to the sternum (For full details of the EMG procedure, refer to Appendix A).

A 10-point moving average filter was applied to the raw data, before it was then converted into root mean squared (RMS) values. This resulted in all EMG data becoming positive values, and allowed for the mean RMS amplitude of the 1024ms interval to be determined by averaging the data. The value for the ¼ ROM test was normalised to the value recorded during the isometric test performed on the chest. This resulted in a percentage amplitude value for the ¼ ROM test, along with an amplitude value for the isometric test in the full ROM position. This allowed for an assessment of changes in neuromuscular activation throughout the ROM. Mean power frequency, along with the EMG activity of the anterior deltoid, was excluded from the study due to poor reliability (see Appendix A). The results of the reliability study also revealed that only the EMG tests performed at the ¼ and chest positions in the ROM produced reliable results. Therefore, only these two tests were examined.

5.3.3 Statistical Analysis

All statistical analysis was performed using SPSS Version 14 (SPSS, U.S.A.). After confirmation of data sphericity (lower-bound epsilon >0.75) and equal variance (Levene Median Test), statistical analysis consisted of 2 x 2 (group x test) repeated measures ANOVAs for each measurement, with a significance level set at $p<0.05$. This was performed to detect any changes between or within groups and/or testing sessions. Multiple repeated measures ANOVA's were chosen for statistical analysis because each of the dependent variables measured were of autonomous interest (Vincent, 1995). Fischers' LSD *post hoc* tests were performed on the means of the data in the event of a significant main effect or interaction.

5.4 RESULTS

The pre- and post-intervention results, including statistical analysis, are provided in table form in chronological order of test. The *post hoc* findings of any significant main effects or interactions that are of major importance to this study have also been presented in figures, while other *post hoc* findings deemed less important by the primary investigator are provided in written form. In addition, the reliability (R) values for each test, based on ICC statistics determined during the reliability study (see Appendix A), are presented in each table.

Table 5.3 contains the subject's body mass pre- and post-intervention. A significant main effect (F=11.00, p=0.004) for testing session was observed, with the subjects in both groups decreasing their total body mass.

Table 5.3. Body mass (±SD) pre- and post-training intervention.

GROUP	PRE	POST	EFFECT FOR TEST	INTER-ACTION
Body Mass (kg)				
VROM	96.3 ± 12.0	94.7 ± 10.8	F = 11.00 p = 0.004*	F = 1.39 p = 0.254
CON	92.8 ± 12.7	91.9 ± 11.4		

* = indicates a significant main effect (p<0.05)

Table 5.4 contains the results for muscle architecture and MTS. A significant main effect for testing session was observed for both the proximal (F=9.37, p=0.007) and distal (F=9.02, p=0.008) muscle thickness measures, with a decrease in muscle thickness detected. No significant differences between groups were revealed in the *post hoc* analysis.

Table 5.4. Musculotendinous stiffness of the upper body pressing movement and architectural properties of the long and medial heads of the triceps brachii pre- and post-training intervention (±SD).

GROUP	PRE	POST	EFFECT FOR TEST	INTER-ACTION
Musculotendinous stiffness ($N \cdot m^{-1}$) (TE=3377.5)				
VROM	19887 ± 4616	17657 ± 4243	F = 0.21 *p* = 0.654	F = 0.34 *p* = 0.570
CON	20176 ± 10821	20440 ± 8586		
Proximal muscle thickness (cm) (TE=0.1)				
VROM	2.5 ± 0.4	2.4 ± 0.5	F = 9.37 *p* = 0.007*	F = 1.91 *p* = 0.184
CON	2.2 ± 0.4	2.1 ± 0.4		
Distal muscle thickness (cm) (TE=0.1)				
VROM	2.4 ± 0.5	2.3 ± 0.5	F = 9.02 *p* = 0.008*	F = 1.76 *p* = 0.201
CON	2.1 ± 0.4	2.0 ± 0.4		
Proximal pennation angle (^{o}) (TE=1.23)				
VROM	8.7 ± 1.3	8.3 ± 0.7	F = 3.50 *p* = 0.078	F = 0.27 *p* = 0.612
CON	9.1 ± 1.0	8.5 ± 1.0		
Distal pennation angle (^{o}) (TE=1.08)				
VROM	9.1 ± 1.2	8.9 ± 1.3	F = 0.44 *p* = 0.515	F < 0.01 *p* = 0.974
CON	9.5 ± 1.1	9.3 ± 1.1		

* = indicates a significant main effect ($p<0.05$)

Table 5.5 provides the results for the isokinetic bench press tests. A significant interaction (F=4.83, *p*=0.047) between testing session and group was found for full ROM isokinetic peak force. *Post hoc* analysis revealed that the VROM group significantly enhanced their peak force values between the pre- and post-intervention testing sessions (10.5% increase in peak force, *p*=0.032). Significant main effects were also observed for testing session, with significant increases in peak force in the third (F=5.04, *p*=0.043) and fourth (F=6.40, *p*=0.025) quarter of the ROM. These significant increases for testing session occurred despite the negligible change in performance observed for the CON group (Change in third quarter peak force: VROM = 10.8%

increase, CON = 3.8% increase, change in fourth quarter peak force: VROM = 13.5% increase, CON = 0.1% increase). The dominance of the VROM improvement was observed in the significant interaction (F=6.21, p=0.027) for peak force results in the fourth quarter of the ROM, with *post hoc* analysis revealing that the VROM group significantly increased peak force during this phase of the movement (13.5% increase, p=0.003). The results for peak force in each quarter of the ROM are provided in Figure 5.3.

Table 5.5. Isokinetic testing results pre- and post-training intervention (±SD).

GROUP	PRE	POST	EFFECT FOR TEST	INTER-ACTION
Isokinetic time to 2nd force peak (ms) (TE=15.24)				
VROM	707 ± 87	657 ± 94	F = 0.44	F = 0.38
CON	720 ± 68	718 ± 176	p = 0.517	p = 0.546
Isokinetic peak force (N) (TE=109.95)				
VROM	1357 ± 198	1499 ± 249	F = 1.19	F = 4.83
CON	1396 ± 286	1348 ± 298	p = 0.295	p = 0.047#
Isokinetic half ROM peak force (N) (TE=118.91)				
VROM	1608 ± 283	1688 ± 275	F = 0.13	F = 0.89
CON	1406 ± 415	1371 ± 294	p = 0.724	p = 0.364
Isokinetic peak force (N) in each quarter: second quarter (N) (TE=93.89)				
VROM	980 ± 180	1004 ± 118	F = 0.56	F = 0.02
CON	1008 ± 179	1043 ± 234	p = 0.466	p = 0.886
Isokinetic peak force (N) in each quarter: third quarter (TE=118.71)				
VROM	1199 ± 166	1329 ± 169	F = 5.04	F = 1.22
CON	1168 ± 213	1212 ± 307	p = 0.043*	p = 0.289
Isokinetic peak force (N) in each quarter: fourth quarter (TE=61.93)				
VROM	1320 ± 193	1498 ± 250	F = 6.40	F = 6.21
CON	1282 ± 276	1283 ± 280	p = 0.025*	p = 0.027#

* = indicates a significant main effect (p<0.05)
\# = indicates a significant interaction (p<0.05)

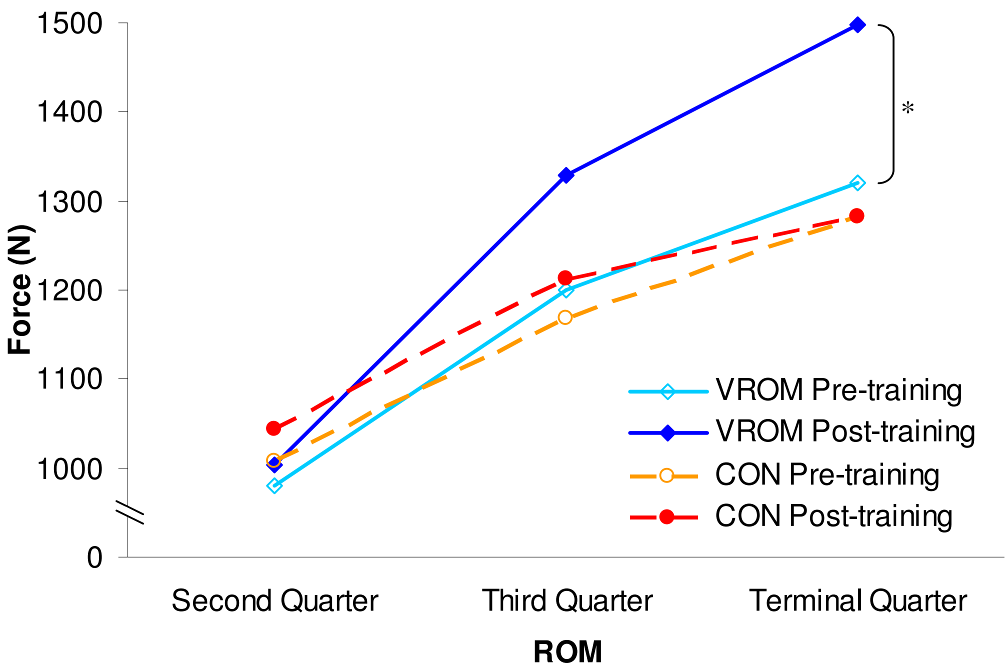

Figure 5.3. Individual quarter peak force *post hoc* results during the full ROM isokinetic bench press.
* Indicates a significant (*p*=0.003) increase in peak force post-intervention in the VROM group during the terminal quarter of the ROM.

Table 5.6 provides the results for the ballistic bench throw tests. Significant interactions between testing session and group were found for full ROM bench throws performed from a countermovement and static-start. The VROM group significantly improved performance in both of these tests post-intervention (countermovement bench throws: 15.5% increase, *p*=0.002, static bench throws: 15.2% increase, *p*=0.012). In addition, the VROM group recorded a significantly superior bench throw displacement than the CON group in the post-intervention tests (26% greater displacement, *p*=0.045), despite no significant difference between groups in the pre-intervention trials (VROM 5.1% greater displacement, *p*=0.702). No significant differences were observed for the CON group post-intervention. The results of the *post hoc* tests for this analysis are provided in Figures 5.4 and 5.5.

Table 5.6. Ballistic bench throw testing results pre- and post-training intervention (±SD).

GROUP	PRE	POST	EFFECT FOR TEST	INTER-ACTION
Countermovement bench throw (cm) (TE=1.33)				
VROM	14.3 ± 3.4	16.5 ± 3.5	F = 4.58	F = 11.05
CON	13.6 ± 4.6	13.1 ± 3.4	p = 0.047*	p = 0.004#
Static bench throw (cm) (TE=1.91)				
VROM	13.9 ± 4.2	16.0 ± 4.1	F = 0.95	F = 9.49
CON	13.2 ± 4.5	12.1 ± 4.1	p = 0.343	p = 0.007#
Half ROM static throw (cm) (TE=1.61)				
VROM	14.4 ± 3.8	16.0 ± 3.2	F = 0.25	F = 1.09
CON	13.1 ± 5.3	12.5 ± 3.0	p = 0.623	p = 0.311

* = indicates a significant main effect (p<0.05)
# = indicates a significant interaction (p<0.05)

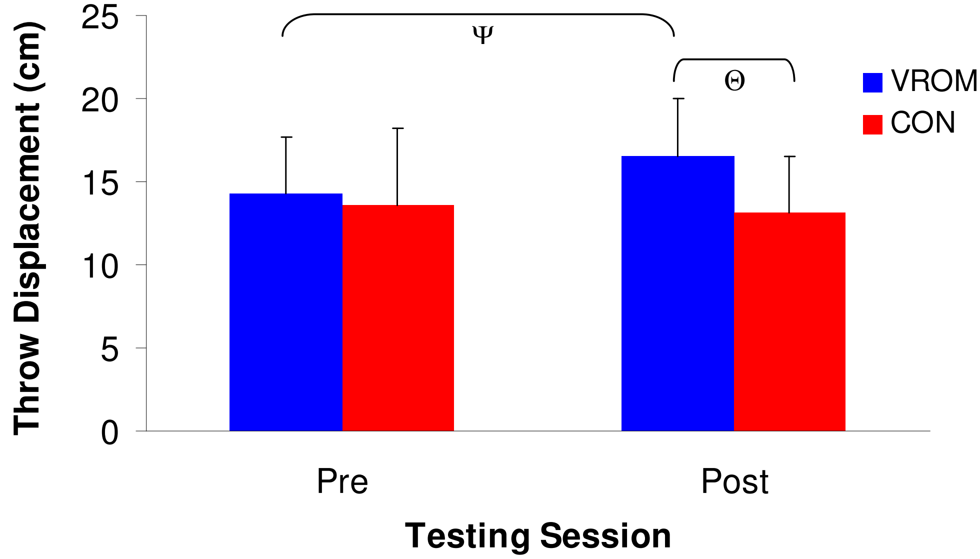

Figure 5.4. Countermovement bench throw displacement (+SD) pre- and post-training intervention.

Subject group x testing session interaction *post hoc* results for countermovement bench throw displacement pre- and post-training intervention.

Θ Indicates a significant difference between groups (p=0.045) for bench throw displacement, with the VROM group throwing significantly higher.

Ψ Indicates a significant difference between tests (p=0.002) for bench throw displacement, with the VROM group significantly increasing performance post-intervention.

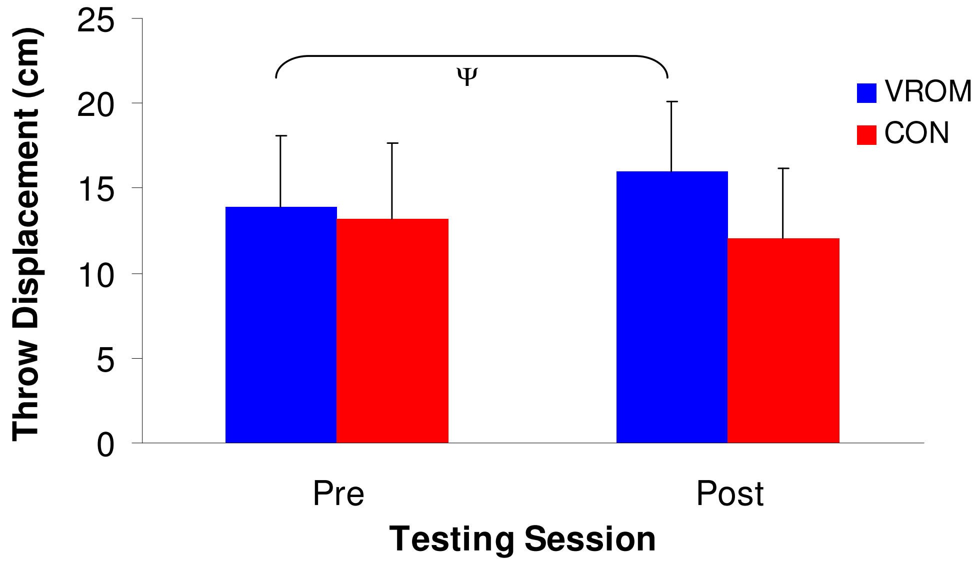

Figure 5.5. Static-start bench throw displacement (±SD) pre- and post-training intervention.
Subject group x testing session interaction *post hoc* results for static-start bench throw displacement pre- and post-training intervention.
Ψ Indicates a significant difference between tests (p=0.015) for bench throw displacement, with the VROM group significantly increasing performance post-intervention.

Finally, the results for isometric strength and EMG are provided in Table 5.7. A significant main effect of testing session was identified during the ¼ ROM isometric tests, with both groups increasing peak force in the second testing session. A significant effect for testing session was also revealed for EMG, with both groups recording an increase in mean EMG amplitude for the pectoralis major during the isometric contraction performed at the chest level. No significant interactions were observed.

Table 5.7. Isometric bench press and electromyographical testing results pre- and post-training intervention (±SD).

GROUP	PRE	POST	EFFECT FOR TEST	INTER-ACTION
Isometric bench press ¼ ROM peak force (N) (TE=278.22)				
VROM	2059 ± 4389	2131 ± 242	F = 6.89	F = 2.07
CON	1652 ± 306	1900 ± 196	*p* = 0.018*	*p* = 0.168
Isometric bench press ½ ROM peak force (N) (TE=153.10)				
VROM	1772 ± 315	1767 ± 174	F = 2.34	F = 2.62
CON	1549 ± 225	1713 ± 262	*p* = 0.144	*p* = 0.124
Isometric bench press ¾ ROM peak force (N) (TE=84.02)				
VROM	1410 ± 205	1442 ± 266	F = 0.64	F = 0.03
CON	1384 ± 222	1405 ± 242	*p* = 0.435	*p* = 0.857
Isometric bench press chest peak force (N) (TE=110.94)				
VROM	1359 ± 281	1389 ± 299	F = 0.28	F = 0.04
CON	1274 ± 186	1287 ± 209	*p* = 0.603	*p* = 0.841
Isometric ¼ ROM EMG - pectoralis major amplitude (%) (TE=30.87)				
VROM	130.5 ± 29.9	131.7 ± 31.1	F = 0.76	F = 0.38
CON	140.5 ± 62.8	136.3 ± 72.9	*p* = 0.398	*p* = 0.694
Isometric ¼ ROM EMG - triceps amplitude (%) (TE=46.62)				
VROM	140.3 ± 45.3	174.6 ± 79.5	F = 0.32	F = 0.92
CON	170.1 ± 71.7	147.3 ± 42.9	*p* = 0.581	*p* = 0.424
Isometric Chest EMG - pectoralis major amplitude (μV*10^2) (TE=0.28)				
VROM	2.46 ± 1.43	2.96 ± 1.76	F = 5.65	F = 0.02
CON	2.55 ± 1.60	3.04 ± 1.90	*p* = 0.032*	*p* = 0.980
Isometric Chest EMG - triceps amplitude (μV*10^2) (TE=1.40)				
VROM	2.74 ± 1.94	2.52 ± 1.09	F = 0.08	F = 0.36
CON	5.02 ± 3.57	3.57 ± 3.07	*p* = 0.785	*p* = 0.707

* = indicates a significant main effect (*p*<0.05)

5.5 DISCUSSION

The results of this study suggest that VROM resistance training provides beneficial functional performance adaptations in resistance trained athletes. Significant increases in ballistic bench throw displacement both with and without prior countermovements, and isokinetic full ROM peak force were all produced in response to the VROM training intervention. These findings support the proposed outcomes of Hypotheses 1 and 2.

While these results revealed the benefits of VROM training in regards to ballistic power, the most interesting findings were in relation to the peak force levels produced in the different phases of the isokinetic ROM. The VROM intervention skewed the force curve towards the terminal phase of the ROM, with the VROM group producing significantly higher peak force values during the terminal phase of the ROM as a result of the training intervention. In contrast, the performance of the CON group was only marginally improved. This would be expected based on the subject's extensive resistance training experience, and overall compares closely with the expected strength increase discussed in the methodology.

The dramatic increase in dynamic peak force near terminal extension may explain why previous studies examining partial ROM training have found only limited results. The previous studies by Massey *et al.*, (2004; 2005) found that partial ROM training produced, at best, similar gains in full ROM strength levels. However, the results of the present study suggest that the benefits of VROM training are more pronounced at shorter muscle lengths. Due to the 'sticking region' of the bench press occurring at long muscle lengths (Elliott *et al.*, 1989), it would appear that a full ROM

1RM strength test would therefore be severely limited in its ability to detect changes as a result of a partial or VROM training intervention. Furthermore, the studies performed previously by Graves *et al.*, (1989; 1992) included isometric strength tests as their criterion performance measures. However, the results of this study suggest that isometric strength is not significantly altered as a result of VROM resistance training, which did not support the outcomes proposed in Hypothesis 3. This theory is somewhat supported by previous research, which suggests only a limited relationship between isometric strength and dynamic performance (Murphy and Wilson, 1996).

Although the results of the present study provide evidence of the benefits of VROM training, the actual mechanisms behind the enhanced performance gains are unknown. No significant differences between groups were observed for MTS or pennation angle, which suggests that these factors were not major contributors to the change in performance. While a significant main effect for test for both muscle thickness and pectoralis major amplitude at the chest was observed, the fact that there were no significant differences between groups suggests that the effect of the changes in these variables on performance was also limited. This did not support the outcome proposed in Hypothesis 4.

In regards to the muscle thickness measures, a significant decrease in muscle thickness was observed between the pre- and post-intervention tests. Due to the increase in performance for the VROM group, it is unlikely that the decrease in muscle mass was due to fascicle atrophy. A possible explanation for the decrease in muscle thickness was the stage of the subject's training cycle, which corresponded with an increase in the intensity of the subject's cardiovascular training program. This may have affected the results of the ultrasound scans in two ways. Firstly, the intra-muscular adipose tissue level may have decreased, resulting in the muscle thickness measures decreasing without a change in the actual thickness of the contractile components. Secondly, the subjects may have been tested in a less hydrated state than during the initial test, due to increased fluid loss during training. This may have decreased the intramuscular fluid levels, once again resulting in a decreased muscle thickness measure. Although no direct measure of body fat percentage was performed, both subject groups lost a significant amount of body mass during the five weeks between testing sessions. In spite of this, the subjects were able to maintain or, in the case of the VROM group, increase performance in the physical tests. This would suggest that the loss of lean muscle mass would have been at most a minimal contributor to the loss of body mass.

Although the current findings prevent any definitive discussion of the mechanisms involved, the leftward shift in the muscle's force/length relationship suggests that the performance benefits may be due to changes in resting muscle fascicle and/or sarcomere length. These architectural changes have been proposed as a method of creating a rightward shift in the muscle's force/length relationship (Proske and Morgan, 2001). For example, previous research shows that performing repeated isometric contractions at long muscle lengths results in dramatically reduced force output at shorter muscle lengths (Philippou, Maridaki and Bogdanis, 2003). It is hypothesised that this adaptation may be a result of the sarcomeres in the midrange of the muscle fascicle becoming overstretched to the point that the actin and mysosin filaments no longer overlap (Proske and Morgan, 2001). This adaptation is often referred to as the 'popping sarcomere' phenomenon (Proske and Morgan, 2001). Due to this increase in length of the midrange sarcomeres, the sarcomeres toward either endpoint of the fascicle then operate with more actin/myosin overlap at any given joint angle. This creates an adaptation that results in the optimal actin/myosin overlap position for force production occurring at longer muscle lengths.

The above mechanism is believed to be responsible for the change in position of concentric peak torque as a result of eccentric overload (Clark *et al.*, 2005; Proske and Morgan, 2001). In regards to VROM training, an adaptation with similar mechanisms but opposite results may occur. In this case, it may be that the sarcomeres at either end of the fascicle are lengthened, and consequently those in the midrange shorten to maintain passive muscle tension. To explain this potential adaptation, during the VROM bench press exercise the majority of sets are performed throughout a limited ROM from terminal extension. The loading used during these partial ROM sets often far exceeds the athlete's full ROM 1RM, potentially resulting in enhanced eccentric intensity suggested by previous research (Mookerjee and Ratamess, 1999). However, the critical difference in regards to the 'popping sarcomere' hypothesis is that it is unlikely that any of the sarcomeres are required to contract during the descending limb of their length/tension relationship. This would remove the potential for overstretching of the sarcomeres to occur, preventing a rightward shift in the muscle's force/length relationship. Although not producing overstretching of the midrange fascicles, the augmented eccentric component, along with the high force levels evident during countermovements, may still result in trauma and subsequent adaptation in both the contractile (sarcomeres) and elastic (collagen in the tendon and potentially titin in the muscle) components.

In this situation, if any damage occurs as a result of eccentric contraction at short muscle lengths it would most likely be to the sarcomeres towards either end-range of the fascicles. These sarcomeres would demonstrate the greatest overlap of the actin and myosin filaments. However, the actual potential for crossbridge attachment sites may be limited due to excessive overlap. Therefore, these sarcomeres may be at the least optimal position for force production of all the sarcomeres in series. If this is the case, these sarcomeres may have the weakest crossbridge strength, and subsequently would be the most susceptible to actin/myosin detachment and damage during the eccentric and countermovement phase of the lift. Consequently, these end-range sarcomeres may adapt to the trauma by increasing their resting length. This would result in a more efficient actin/myosin overlap position for force production at short muscle lengths, in an attempt to prevent subsequent trauma occurring as a result of the limited ROM contractions. However, if an identical muscle and tendon length was evident after this adaptation there would be less sarcomere length deviation along the muscle fascicle. If the end-range sarcomeres lengthen while the fascicle length remains the same, the midrange sarcomeres would be required to shorten. This increased similarity in sarcomere length would result in a more parabolic force curve, with a higher peak occurring at a distinct section of the ROM. This would be due to all of the sarcomeres reaching their optimal length in a similar phase of the ROM, an adaptation that appears unlikely for the VROM group because there were no dramatic reductions in force throughout the ROM in comparison with the CON group.

This parabolic force curve may have been overcome by an increase in tendon stiffness, which has been found to occur as a result of eccentric training (LaStayo, Woolf, Lewek, Snyder-Mackler, Reich and Lindstedt, 2003). In fact, maintaining identical sarcomere length deviation, along with muscle and tendon length, but increasing tendon stiffness would result in similar findings in the terminal phase of the ROM to those observed in the present study. This adaptation would result in shorter tendon and longer muscle lengths throughout the movement, because a stiffer tendon would exhibit less stretch (Lichtwark, Bougoulias and Wilson, 2007). Therefore, the muscle would contribute more to the musculotendinous length change.

If this suggestion is correct, it would support the use of VROM training in comparison to partial ROM training in only a single, limited range of the movement. Performing partial ROM training in only the strongest ROM requires high force production in only a single countermovement position. This may result in sarcomere length or tendon stiffness adaptations, as discussed previously, that would be severely biased towards force production at short muscle lengths. However, the problem with this adaptation is that at long muscle lengths, a greater ratio of the sarcomeres may be required to contract during the descending limb of the length tension relationship. Subsequently, the potential damage associated with trauma to the sarcomeres during eccentric contractions at long muscle lengths would be elevated. This adaptation could then increase the risk of muscle strains and tears.

In contrast, the use of VROM training, with countermovements performed throughout the ROM, may limit this negative effect. The sarcomeres in the fascicle and/or tendon stiffness levels would be more likely to adapt in a way that optimises force production throughout the ROM, potentially overcoming the force production bias of the partial ROM only resistance training. Examples explaining these theories are provided in Figures 5.6 and 5.7.

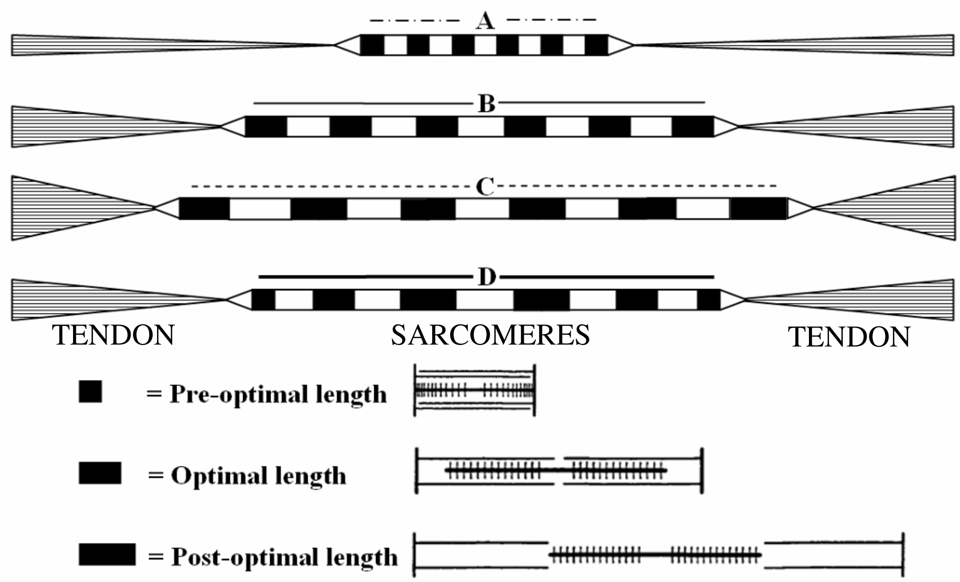

Figure 5.6. The effect of changes in tendon stiffness and/or sarcomere length on fascicle force production in the midrange of the movement.

A Represents a fascicle bridging two over-compliant tendons. In this phase of the ROM the fascicles will not be producing optimal force due to excessive overlap of the actomyosin complex.

B Represents a fascicle bridging two tendons with a stiffness level that results in the fascicles reaching optimal force production at this position in the ROM.

C Represents a fascicle bridging two under-compliant tendons. In this phase of the ROM the fascicles will not be producing optimal force due to limited overlap of the actomyosin complex.

D Represents a musculotendon system with tendon stiffness and heterogenous sarcomere lengths that would optimize force production throughout the entire ROM.

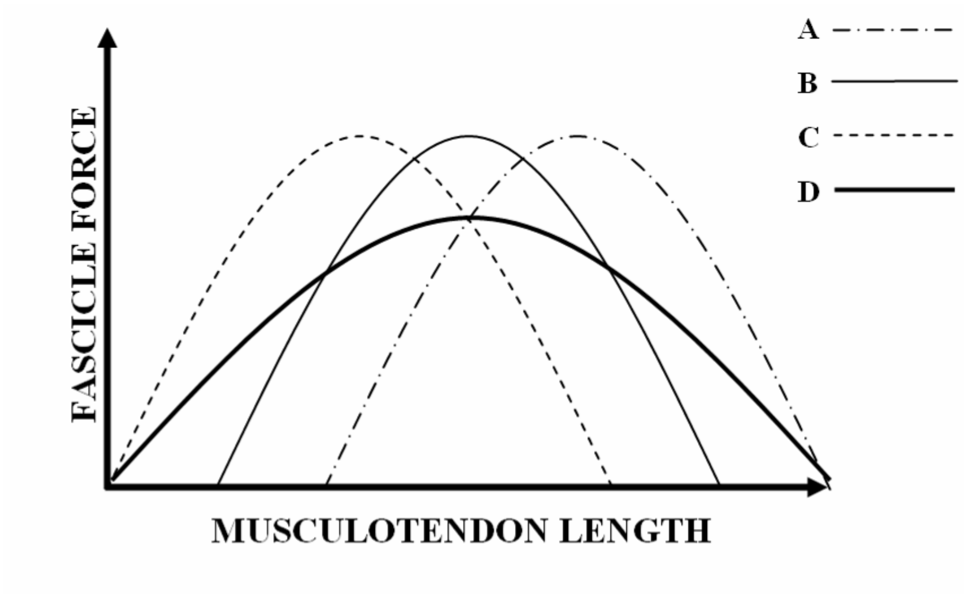

Figure 5.7. The fascicle force/muscle length relationship of the musculotendon systems from Figure 5.6.

A Optimal force production at longer muscle lengths, poor ability at shorter lengths.

B Optimal force production in the midrange of the musculotendon length, poor ability at longer and shorter lengths.

C Optimal force production at shorter muscle lengths, poor ability at longer lengths.

D Peak force production below those of A,B and C. However, the force curve is plateaued, allowing for maintenance of force production at all lengths. A similar force curve would be apparent if the fascicles in a muscle group contained homogenous intra-fascicle sarcomere lengths but heterogeneous inter-fascicle sarcomere lengths. This may be the most likely adaptation as a result of a VROM training intervention.

As demonstrated in Figure 5.7, a combination of heterogeneous inter- and/or intra-sarcomere lengths would result in changes to the muscle's force/length relationship. These adaptations would be biased towards producing higher force levels throughout a wider region of the ROM. However, it could also reduce peak force levels, which was not evident in the results of the present study. In fact, force production at long muscle lengths did not vary between the VROM and CON training groups despite the improvements for the VROM group at shorter muscle lengths. This suggests that the efficiency of the movement was enhanced, possibly by a combination of discrete sarcomere length changes and alterations to dynamic muscle activation only in the motor units that possess the leverage characteristics that would result in them being predominantly utilised at short muscle lengths. This would result in only minimal adaptations in the motor units which are leveraged towards force production at long muscle lengths, and therefore only a negligible change in force production in this ROM despite the dramatic changes in force production at shorter muscle lengths. This is the exact performance adaptation that was observed in the results of the present study. However, whether any of these adaptations took place was beyond the scope of the current study, and would be very difficult to examine accurately in human subjects.

5.6 CONCLUSION

The inclusion of a VROM resistance training microcycle into an athlete's training program provides superior strength and dynamic force improvements in comparison with performing strictly full ROM training. This method of training appears to be a key component in an athlete's attempt to achieve their optimal sporting performance.

4.7 IMPLICATIONS ON THE GOAL OF THIS THESIS

The primary hypothesis of this thesis is that VROM training will result in significantly greater strength and power performance throughout the entire ROM, especially as the ROM diminishes towards full extension, due to the increased efficiency resulting from training each phase of the movement at near maximal levels. The results of the current study show that ballistic power and isokinetic strength improved during the full ROM movements. The analysis of isokinetic peak force in distinct phases of the ROM suggested that the benefits of VROM training were augmented as the ROM of the exercise was reduced. These findings imply that the proposed outcomes suggested in the primary hypothesis were supported by the results of current study.

Chapter 6

CONCLUSIONS AND PRACTICAL APPLICATIONS

6.1 SUMMARY

The results of the series of experiments contained within this thesis suggest that variable ROM (VROM) resistance training provides numerous performance benefits when compared to traditional, full ROM training. These advantages are evident both within a single session and in regards to longitudinal gains. The within-session benefits include the production of peak force in four separate phases of the ROM, which is more functionally specific. In addition, significantly greater peak forces are recorded in the limited ROM sets due to the increase in load, which may better prepare athletes for facing high external loading in their athletic events. The longitudinal gains include an increase in full ROM peak and explosive force production, resulting in enhanced athletic performance. This increase in performance is likely due to a distortion of the force curve, resulting in enhanced force production towards the terminal phase of the ROM.

Although the results of this thesis provide definitive evidence of the advantages of VROM over traditional full ROM resistance training, the actual mechanisms behind these benefits are still somewhat unclear. No changes in muscle architectural features, neuromuscular firing patterns or musculotendinous stiffness were observed. However, based on the alterations to the isokinetic force curve, one theory that may explain the performance gains is an adaptation in tendon stiffness and/or sarcomere lengths. Due to traditional full ROM resistance training comprising the sticking region of the lift in an identical position for each repetition and set, the trained athlete may have sarcomere lengths and/or tendon stiffness properties that are biased towards optimal performance only at this point. In contrast, VROM training results in sticking regions occurring at four different positions in the ROM. Therefore, any architectural properties cannot be biased towards optimal performance at only one position in the ROM.

These potential mechanisms for the improvement in performance in response to VROM training are by no means definitive. However, they do provide a plausible mechanism behind the rapid alterations in the force/ROM profile of the subjects in response to a five week training intervention.

This study adds to the current knowledge concerning the performance of resistance training in a limited ROM, and is the most in-depth analysis of this area to date. Future research should focus on the combination of this method of training with ballistic power exercises, as these two forms of training used conjointly could provide synergistic benefits to athletes. Studies examining the incorporation of this method of training into a training program spanning numerous years would also provide further evidence of its potential to enhance athletic performance.

6.2 PRACTICAL APPLICATIONS

Variable ROM training should become a component in the preparation of high level athletes participating in any sport where the performance of powerful movements is required. The numerous benefits of VROM training may help to optimize the transfer of strength gains in the weights room to athletic performance on the sporting field. This study specifically targeted the upper body pressing movement, however it is plausible that the advantages of this training program would transfer effectively to lower-body resistance training programs.

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Appendix A

EXTENDED METHODOLOGY AND RELIABILITY TESTING

A.1 INTRODUCTION

The aim of this thesis was to compare the effects of a full ROM vs. variable ROM (VROM) resistance training program on athletic performance. However, before commencement of any data collection it was necessary to determine the most appropriate methods of assessing the proposed outcomes. The outcome measures deemed important for determining the effectiveness of the training intervention included:

1. Muscle architecture and size
2. Muscle mechanics
3. Maximal voluntary concentric strength during resisted contractions
4. Ballistic performance with and without elastic energy contribution
5. Maximal voluntary isometric strength throughout the ROM
6. Eccentric force production

Due to the time constraints involved when working with athletes, it was essential that the tests performed were both valid to the proposed outcomes of the study and that each test examined a separate mechanical or performance property. Furthermore, because the athletes who were involved in the training study were participating in a pre-season program that involved sport-specific training between five and six days a week, invasive measures such as muscle biopsies were excluded.

The athletes involved in the training study were professional rugby league players participating in a lower body anaerobic endurance/upper body muscular power microcycle. Due to this stage of the training cycle, the intervention was restricted to the upper body bench press movement in an effort to reduce the potential for the lower-body anaerobic endurance training to affect the results of the intervention. Therefore, the testing methods were required to be valid for upper body pressing movements and the musculature involved.

In the next section, the testing protocols implemented to examine each of the primary outcome measures will be discussed. This section will focus on the specific reasons why each test was chosen. The protocol for each test will then be outlined in the methodology section.

1. Muscle architecture and size

Test – Ultrasound (ULT) scans to assess the pennation angles and muscle thickness of the long and medial heads of the triceps brachii.

Assessment of muscle architecture allows for an *in vivo* examination of the structural properties of the muscle. Previous research suggests that muscle architecture may have more influence on the ability to perform dynamic contractions than muscle fibre type (Burkholder *et al.*, 1994; Sacks and Roy, 1982). Furthermore, architecture of the long and medial heads of the triceps brachii has been previously performed (Kawakami *et al.*, 1993), and these muscles are known prime movers in the bench press exercise (Elliott *et al.*, 1989).

2. Muscle mechanics

Test 1 – Musculotendinous stiffness (MTS) of the bench press musculature.

The stiffness of the musculotendinous unit is correlated with upper body performance (Wilson *et al.*, 1994), and may also be a factor in muscle and tendon strain injuries (LaStayo *et al.*, 2003). The upper body MTS test is based on the damped oscillation response which occurs after an external perturbation with the subject in the bench press position. This test has been previously used in both cross-sectional and training studies (Shorten, 1987; Wilson, Elliott and Wood, 1992; Wilson *et al.*, 1994; Wilson, Wood and Elliott, 1991), and is a mechanical measure of the systems rigidness when an external force is applied. Therefore this test was chosen as a measure of upper body muscle mechanics.

Test 2 - Mean power frequency and normalised integrated amplitude electromyography (EMG) of the pectoralis major, long head of the triceps brachii and the anterior deltoid during maximal voluntary isometric contractions.

Mean power frequency provides a measure of the frequency of motor unit firing. It has been previously suggested that this provides a non-invasive estimation of the muscle fibre composition and its contribution to the examined movement (De Luca, 1997). In contrast, normalised integrated amplitude analysis of the EMG signal provides a measure of the amplitude of the motor unit excitation (De Luca, 1997; Konrad, 2005) and is typically regarded as a measure of the intensity of the contraction performed (De Luca, 1997). These methods were chosen in preference to invasive techniques of muscle fibre type (using muscle biopsies) and neuromuscular signal (using in-dwelling electrodes) assessment.

3. Maximal voluntary concentric strength during constant velocity contractions

Test – Full ROM peak and mean force, and force production in each specific ROM during isokinetic bench press.

Although no sporting actions could be deemed purely isokinetic in nature, this form of contraction allows for an examination of the force curve while reducing the confounding effects of acceleration. Isokinetic assessment allows for a valid comparison of force output in specific areas of the ROM between tests and subjects. In addition to isokinetic values measured during full ROM contractions, it was also deemed important to examine the result of isokinetic contractions performed with the countermovement in the midrange of the ROM. This allowed for the examination of force output in a situation where the muscle fascicles had not been pre-stretched beyond half the ROM, a situation that often occurs during sporting movements. Therefore, both full ROM and terminal half ROM isokinetic strength tests were performed.

4. Ballistic performance with and without elastic energy contribution

Test – Throw displacement, peak and mean force and time to peak force during dynamic bench throws.

The capacity to produce explosive force is necessary in numerous sporting events (Burke *et al.*, 1980; Fry and Kraemer, 1991; Mahood *et al.*, 2001; Sawyer *et al.*, 2002). Ballistic bench throws are commonly used to assess explosive force (Newton *et al.*, 1996; Newton *et al.*, 1997), and whilst utilising the same movement patterns as the bench press, this test requires the subject to propel the barbell for maximum displacement at the end of the lift.

In contrast, performing the throw with a concentric only contraction, which removes the contribution of elastic energy to the movement, is achieved during a static-start ballistic throw. This test is performed by nullifying the descent phase of the barbell using a braking system such as the Plyopower™. This system allows for the barbells' mass to be removed in all phases of the exercise, with the exception of the concentric movement. These two tests provide a measure of ballistic force potential with and without elastic strain energy contribution, and therefore were chosen as measures of ballistic muscle performance.

5. Maximal voluntary isometric strength throughout the ROM

Test – Ramp protocol isometric peak force at each quarter of the ROM

Peak isometric force provides a measure of an athlete's potential to produce maximal force in a situation where the external load is immoveable, and has been incorporated in previous studies examining the efficacy of partial ROM training (Graves *et al.*, 1989; Graves *et al.*, 1990). For this study, a ramp protocol where the level of contractile force was gradually increased was deemed necessary for the subjects to reduce the risk of shoulder joint injury. The nature of the experimental intervention also required that the isometric test be performed at different phases of the ROM, because previous research shows that ROM specific isometric strength gains are restricted to within approximately 20% of the ROM trained (Gardner, 1963; Lindh, 1979). Therefore, it was considered necessary to perform isometric strength tests at each quarter of the ROM, corresponding to tests at the chest, three quarter (¾), one half (½) and one quarter (¼) of the ROM from terminal extension. This provided a minimal likelihood of overlapping the tests, while still being able to detect any ROM specific changes in performance. Therefore, a five second ramp protocol at each quarter of the ROM was performed to assess maximal voluntary isometric strength.

6. Eccentric force production

Test – No satisfactory test was found

Although eccentric force production may have been altered by the training intervention, no valid test was able to be performed as part of this study. An eccentric drop test, performed previously by Wilson *et al.* (1994) was pilot tested. However, this test produced unreliable results, and was also thought to possess a high risk of injury. Isokinetic eccentric bench press was also trialled, however, the torque generated by the subjects was excessive and may have resulted in malfunction of the isokinetic dynamometer, with the potential for subsequent injury to the participants. Isokinetic elbow extension was deemed non-specific to the movements utilised in the training intervention. Push-up drop tests were also trialled, however once again the results were unreliable. A winch setup, as used previously by Wilson, Walshe and Fisher (1997), was also discussed. This would have consisted of a Smith machine mounted winch used to test isokinetic eccentric strength. However, the investigator rationalised that the risk/reward ratio of including an eccentric strength test in the testing battery was too high, and therefore examination of this attribute was excluded.

Once the tests for each measure were determined, it was necessary to create a protocol for data acquisition and analysis. This aspect of each test is discussed in the following sections.

A.2 METHODOLOGY

A.2.1 Subjects

Eleven subjects volunteered to participate in the reliability study. The participants were professional rugby league players (age: 22.8 ± 2.2 yr, height: 181.3 ± 2.2 cm, mass: 92.65 ± 9.0 kg) who were excluded from the training study, due to sports specific, training history or personal reasons. All subjects completed an informed consent form along with a pre-activity readiness questionnaire. Ethical approval from the Central Queensland University Human Research Ethics Committee was received for this study (approval number H05/09-105).

A.2.2 Experimental Protocol

The testing sessions spanned two consecutive days. Muscle architecture was examined on the first day, with all remaining tests performed during the second session. Neither session was performed the day after an upper body resistance training session. This reliability study only examined same-day test-retest repeatability, not between testing days. This was due to a number of factors such as:

1. Time constraints – At this stage of the training cycle the subjects only had one rest day per week. Therefore, to perform a between-day assessment it would be necessary to perform the second session at least one week after the initial test. This would have resulted in the subjects performing 14 consecutive days of intense training immediately prior to the second testing session. This may have resulted in both physical and mental fatigue that would have adversely affected the results of the study, and more importantly, may have dramatically increased the subject's risk of overtraining and injury.

2. Need for athletic subjects – To determine the reliability of a test it is essential to use subjects in the pilot study with similar characteristics to those that will be tested in the primary study, otherwise the risk of measurement error associated with the subjects is high (Thomas and Nelson, 1996). Therefore, performing a between day reliability assessment in subjects who were not well-trained athletes was rejected.
3. Uncontrollable performance alterations between days – Due to the fact that the subjects were all participating in an intense training program, incorporating an inter-day reliability study would have been seriously hindered by extraneous variables that could not be effectively controlled for. For example, attempting to control for the physical activity performed in the 48 hours prior to each session would have been impossible. Therefore, whether the inter-day changes in results were due to reliability of the test or extraneous factors such as fatigue would have been very difficult to determine.

Although a same-day test-retest method of assessing reliability results in a higher intraclass correlation co-efficient than a separate day test-retest examination, it has been accepted as a satisfactory method of establishing the reliability of physical performance tests (Thomas and Nelson, 1996). Consequently, this method of reliability assessment was undertaken for each of the following tests.

A.2.3 Session 1 – Muscle Architecture

The ULT machine incorporated in this study was an Acuson Antares Premium Edition (Siemens, U.S.A), with a transducer capable of scanning at a resolution of up to 15 MHz. This allowed for considerably more defined images than those performed in previous studies examining muscle architecture using transducers with 7.5 or 5 MHz probes (Blazevich and Giorgi, 2001; Kawakami *et al.* 1993). While it was possible to scan at high frequencies, the large muscle mass of the subjects participating in the study required a trade-off between image clarity, which increases with higher resolution, and depth quality, which decreases with higher resolution (Walker, Cartwright, Wiesler and Caress, 2004). Pilot testing revealed that for these subjects, a testing frequency of 11.4 MHz provided the optimal ultrasound image.

This pilot testing, which incorporated the methods performed previously by both Giorgi, Weatherby and Murphy (1999) and Kawakami *et al.*, (1993), resulted in a testing position that was deemed unreliable for use in a pre- and post-intervention situation. For example, the investigators in the Kawakami *et al.* (1993) study performed the ultrasound assessment with the subjects standing with their arm relaxed by their side, in an extended position. The scan was then performed 40% of the distance from the lateral epicondyle to the acromion process of the scapula. The researchers in the Giorgi *et al.* (2001) study performed a similar testing protocol, however they had the subjects flex their elbow to 90^o and rest their forearm on a bench with the upper arm in a vertical position. The scanning position was at a point midway between the olecranon process and the acromion process. Pilot testing of each of these methods revealed that the belly of the medial and long head muscles was not located at this position, and that the transducer head had to be substantially manipulated until the belly of the muscles was located. Therefore, creating a testing protocol that allowed for high repeatability, and also movement specificity, of the test was necessary. This resulted in the following steps being taken to ensure the validity of the test:

1. The subject was instructed to lie in a prone position on a plinth.
2. The subject then reached out and held a custom made handgrip attachment mounted on a tripod, resulting in them being in an inverted bench press position with the upper arm perpendicular to the spine.
3. The height of the plinth was then electronically adjusted so that the subject's forearm was at a 90^{o} angle with the upper arm, replicating a position in the midrange of the bench press movement. All transducer and musculoskeletal angles were measured using a goniometer with spirit level attachment.
4. A line was then drawn perpendicular to the spinal column along the middle of the upper arm, creating an upper arm midline.
5. The distance from the acromion process to the olecranon process was measured, and a mark placed along the upper arm midline at 40% of this measured distance from the olecranon process.
6. A line perpendicular to this midline was marked around the posterior surface of the arm.
7. Gel was applied to the transducer head, and the probe was moved along this posterior line until the belly of the medial head was located. This was deemed the point at which the combined image of the long and medial heads was thickest. The head of the transducer was moved in a way that it was constantly parallel to the upper arm midline. During this stage, the transducer head was held perpendicular to the surface of the skin. An example of this testing position is contained in Figure A.1.

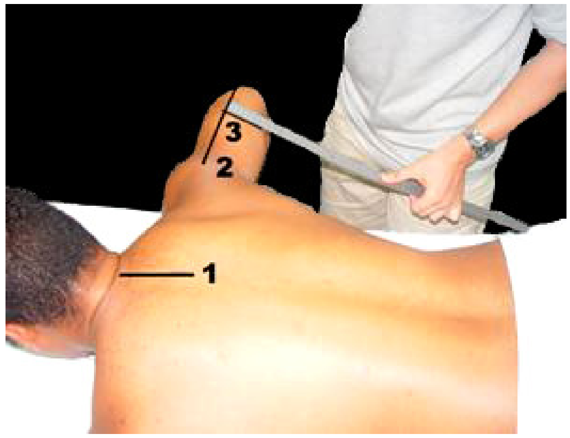


Figure A.1. Determination of ultrasound measurement position.

1 Spinal column.
2 Upper arm midline joining the olecranon process and the upper arm midpoint.
3 40% of the distance from the olecranon process to the acromion process marked along the upper arm midline. From this point a perpendicular line was drawn, on which the ultrasound scan was performed.

8. The angle of the transducer head was then delicately manoeuvred over the skin surface, until the image of the humerus was exactly horizontal on the ultrasound screen. At this point the image was recorded. An example of a triceps brachii image obtained using this procedure is provided in Figure A.2.

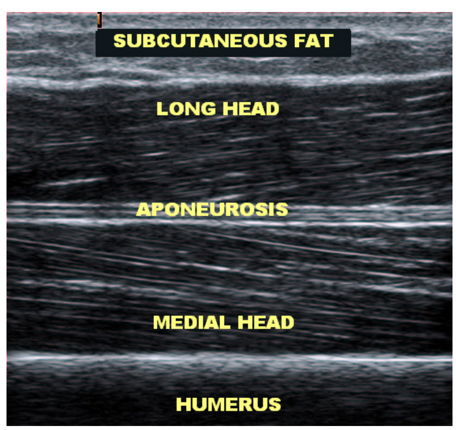


Figure A.2. Example of an ultrasound image of the long and medial heads of the triceps brachii.

This image was obtained by scanning at 11.4 MHz using a linear transducer.

9. The distance from the upper arm midline to the transducer was then measured. The transducer angle in comparison with the horizontal plane was then assessed, using the goniometer with spirit level attachment, and recorded. These steps were taken to ensure repeatability of the testing position. Figure A.3 displays the testing position and the assessment of transducer angle.

Figure A.3. The assessment of transducer angle.
This was performed using a manual goniometer with a spirit level attachment.

<u>Data Analysis</u>

From each test, a single image was obtained as previously shown in Figure A.2. This image was then imported into the Scion Image (Scion Corporation, U.S.A) analysis package, and the architectural properties were examined electronically. Firstly, the image was sharpened to ensure optimal clarity of the image and the scale was set. Secondly, the pennation angles and muscle thicknesses of the proximal and distal portions of the long and medial heads of the triceps brachii were determined using the angle and distance relative to scale functions in the software. Proximal and distal thickness of each muscle was measured by recording the distance from the aponeurosis to the border of the muscle, which for the long head was the border with the subcutaneous fat layer and for the medial head was the border with the humerus, at each edge of the image. Each muscle was then split into a distal and proximal half, with the pennation angle of the three most prominent muscle fascicles with an attachment point in each half recorded. An example of these measurements is provided in Figure A.4. The median of these three results for each half of the muscle was deemed the pennation angle for that section of the muscle.

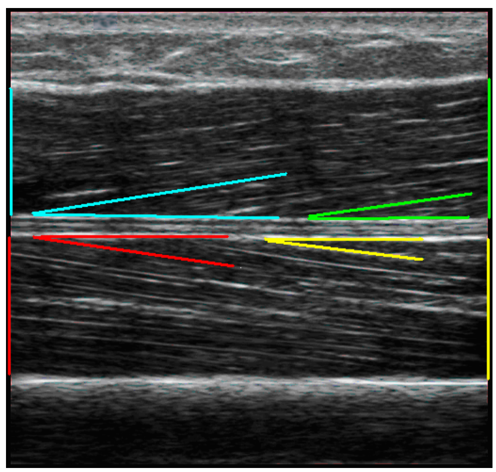


Figure A.4. The assessment of muscle thickness and pennation angles of the triceps brachii long and medial heads.

Blue — Proximal thickness and pennation angle of the long head.
Green — Distal thickness and pennation angle of the long head.
Red — Proximal thickness and pennation angle of the medial head.
Yellow — Distal thickness and pennation angle of the medial head.

<u>Assessment of Reliability</u>

This test was performed twice on the same day to assess inter-trial reliability. Furthermore, previous research has shown that the intraclass correlation coefficients for test-retest reliability of ultrasound assessment of muscle architecture, over separate days using less-advanced equipment, is as high as R=0.998 (Reeves, Maganaris and

Narici, 2004). In addition, previous training studies have also repeated very high test-retest reliability of ultrasound assessment of muscle architecture using both inferior equipment and a less strategised approach to data collection and analysis (Giorgi *et al.*, 1999).

A.2.4 Session 2 - Muscle Mechanics and Performance

Due to the subjects competing in a high level rugby league competition, it was essential for the testing sessions to be as unobtrusive to their training schedule as possible. Therefore, it was necessary to confine all physical testing to one session, resulting in the need for lengthy rest periods between testing phases to reduce the negative effects of fatigue. To achieve this, the subjects were split into randomly assigned pairs for the physical testing session. Although they were assigned to a pair, each subject completed the entire phase of a test before the next subject in the pair started. Once the second subject completed the testing phase, the necessary equipment was swapped and the first subject then began the next testing phase. This allowed for each subject in the pair to achieve as close to optimal recovery as possible. All tests were performed twice to determine reliability. However, for the MTS and isokinetic tests, which the subjects were unfamiliar with, the subjects were allocated time prior to the test to familiarise themselves with the protocol.

During this testing session a number of standardisation tests were performed, along with the biomechanical and performance tests. In chronological order, an overview of the testing session is provided in Figure A.5.

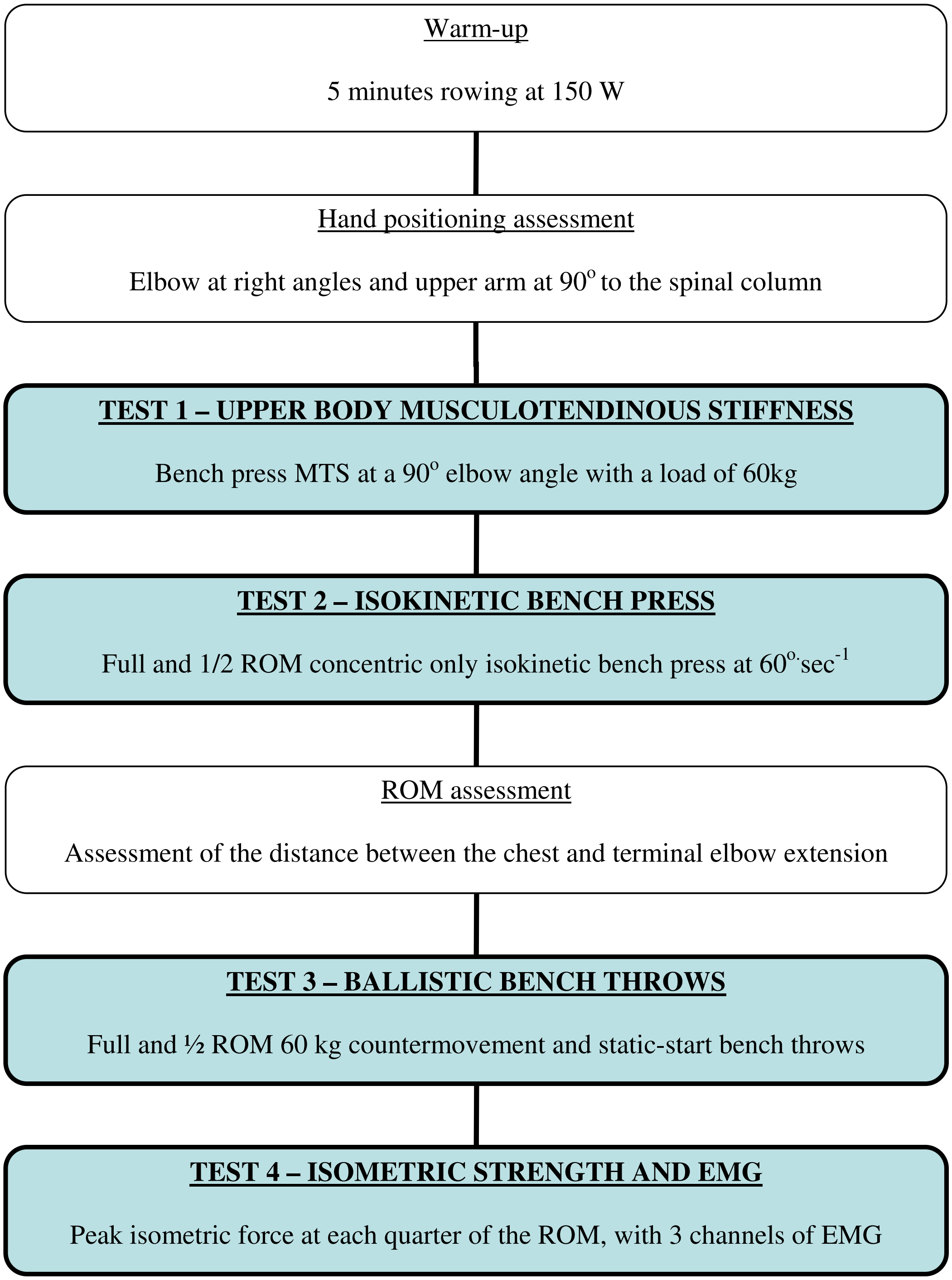
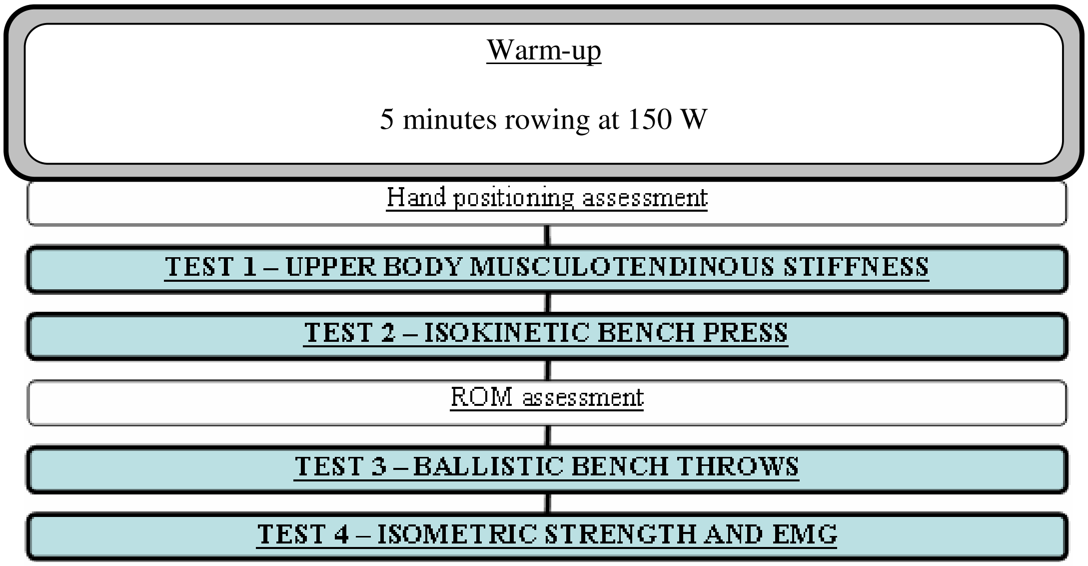


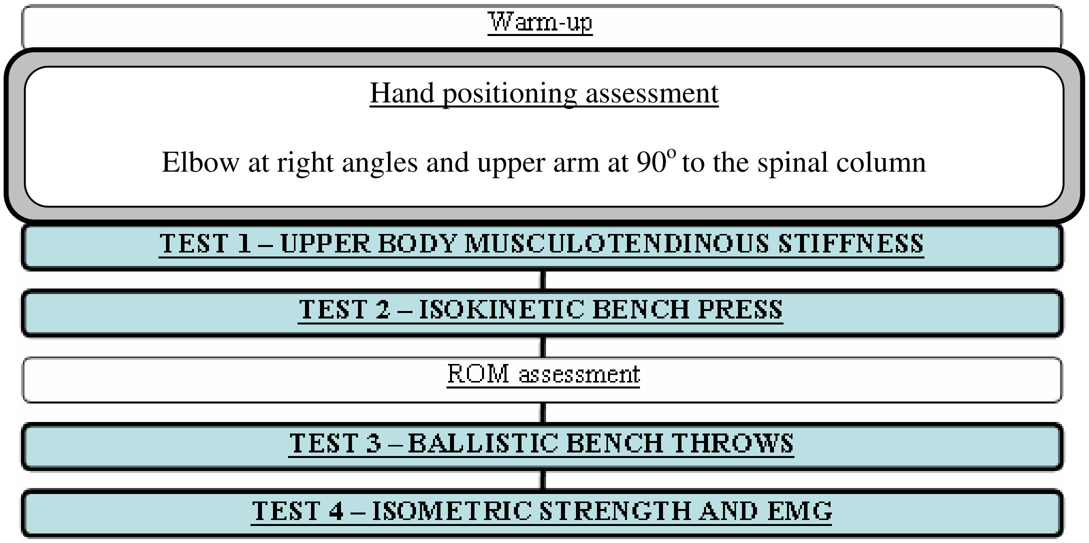
Figure A.5. Flowchart overview of testing session two.
A white background signifies a standardisation test, whereas light blue represents biomechanical and performance tests.

The equipment required and protocol for each test will be examined in chronological order in the following sections. The heading for each section is provided in the flowchart, with the full size segment representing the following section of this article.



Warm-up

Prior to testing, the subjects performed a five minute warm-up on a rowing ergometer, rowing at a steady state 150 Watts for five minutes.



Hand Positioning Assessment

After finishing the warm-up, the subject's standardised hand position during lifting was determined. This was performed to ensure repeatability of the tests, as small changes in hand positioning would have had a dramatic effect on the ROM of the elbow and shoulder joints. Removing changes in the ROM was especially important in regards to EMG, because identical joint angles between trials reduced the risks of assessing different motor units in each test.

The subject's hand positioning was measured and standardised in accordance with the following steps. The subjects were instructed to:

1. Lay on the custom made weights bench in the bench press position and grip the barbell in their natural lifting position.
2. Lower the barbell until their upper arm was parallel to the ground (measured using a goniometer mounted spirit level).

To create a standardised lifting technique, the elbow angle at this position was 90°. If hand positioning was incorrect, the subjects were instructed to place the barbell on the lifting rack and readjust their hand position on the bar. This step was repeated until correct hand positioning was obtained. The correct hand position for each subject was measured using the one centimetre markings on the bar, and recorded on the subject's information sheet. To allow for easy detection of the correct hand position, custom made sliders on the barbell were moved to a point where the inside of the hand was to be placed. An example of this protocol is provided in Figure A.6.

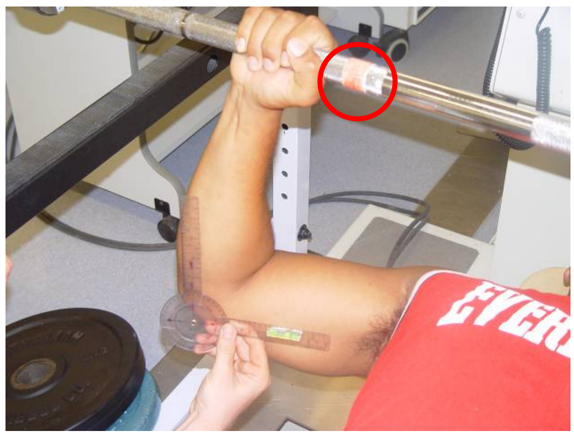
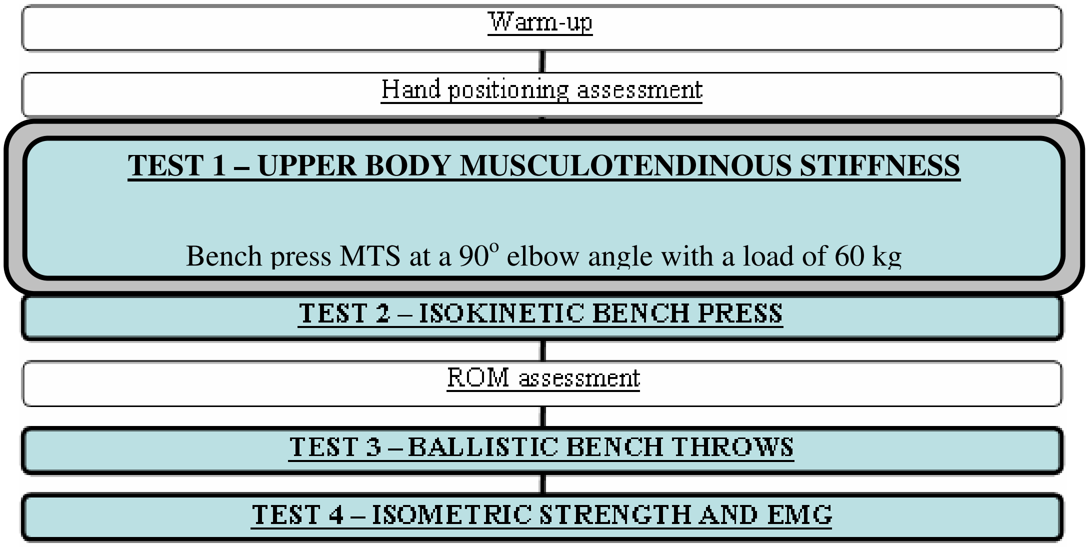


Figure A.6. Setting the correct hand position.
○ Indicates the slider used to set hand position during the subsequent tests.

The subject's hand position measured during this trial was used for all of the performance tests. This was possible because both the free weight and Smith machine barbell, used during the bench throws and isometric strength tests, were marked identically. Once the warm-up and hand position tests were completed the subjects commenced physical testing.



Test 1 - Upper body musculotendinous stiffness (MTS)

The testing equipment consisted of a force plate (Advanced Mechanical Technology Inc., U.S.A.) mounted custom weight lifting bench. The bench was altered to remove all cushioning by replacing the cushioned board with a sheet of medium density fibreboard cut to the same dimensions. The custom made bench was designed with no cushioning to maximise the transfer of force from the subject to the force plate. Furthermore, the bench was also designed so that the base underneath the barbell was only in contact with the force plate, removing the potential for loss of force into the ground surrounding the plate. All aspects of the positioning were measured to ensure that the force produced would be transferred evenly through the force plate. A force plate was used for the assessment of force to remove the errors inherent with equating this variable from distance and time data retrieved from a position transducer. This setup is displayed in Figure A.7.

Figure A.7. Custom made force plate mounted bench press. Cushioning was replaced with an identical dimension sheet of medium density fibreboard. The weights bench was attached in a way that transferred all force from the barbell in a perpendicular vector through the middle of the force plate.

A free weight barbell was used to allow for unrestricted movement of the barbell during the MTS tests, resulting in a more natural oscillation of the upper body. The barbell was placed inside a Power Cage (Calgym, Australia) to ensure the safety of the subjects.

The upper body MTS test was performed using the protocol comprehensively outlined by Wilson *et al*. (1991). This required the subject to statically hold a barbell in the midrange of the bench press movement. A brief perturbation of approximately 100N was then applied to the barbell, with the resulting damped oscillation analysed to provide the mechanical stiffness of the movement.

While the testing protocol of Wilson *et al*. (1991) was replicated for this study, three modifications were made. Firstly, in the Wilson *et al.* (1991) study the testing position was set at approximately 3 cm above the chest. However, in the present study the subject's testing position was at an elbow angle of between 90^{o} and 110^{o}. This allowed for stiffness in the midrange of the movement to be examined, which was a major focus of the training study. Secondly, instead of a series of percentages of 1RM loads, a single absolute load of 60 kg was used. Although somewhat limited, a single absolute load was chosen for a number of reasons.

With respect to the single load, performing multiple MTS tests with varied loads would have resulted in considerable fatigue to the subjects, along with being time consuming. Therefore, a single load was deemed appropriate. In regards to the absolute load, a percentage of predicted 1RM could have been used in this study. However, because the subjects were participating in training programs that were designed to make them stronger, their predicted 1RM strength would most likely have changed in the post-testing session, resulting in a different percentage of their maximal strength being tested in the post-intervention session. Therefore, an absolute load of 60 kg, which was approximately 45% of the subjects in the training studies predicted 1RM, was chosen based on pilot studies showing it provided the most reliable results. While this limited the potential to predict maximal MTS, it still allowed for an assessment of changes in MTS as a result of a training intervention against an identical external load. The third modification to the Wilson *et al.* (1991) protocol was that four tests, plus preparation trials, were performed with one load instead of three. Prior to the testing session, the subjects were instructed and given an example of how to perform the test. They were then allowed trial tests until the tester was satisfied with reliability of the results. The subjects then performed four tests with the absolute load and the median two results were selected for data analysis.

Familiarisation of the MTS tests for the investigator were carried out prior to the testing session, in order to ensure a repeatable perturbation. While the researcher attempted to standardise the testing protocol, incorporating a hand tapping method of perturbating the barbell results in varying force levels between tests. However, this disparity between trials is of little consequence because an elastic system will oscillate at its natural frequency regardless of the magnitude of the applied perturbation (Wilson *et al.,* 1994).

The force/time curves were collected via the custom bench mounted force plate (Advanced Mechanical Technology Inc., U.S.A.). MTS of the two selected trials was analysed using a custom written Labview (National Instruments, U.S.A.) software package that incorporated the damped spring model calculations provided in the McNair *et al.*, (1992) paper. An example of a damped spring oscillation occurring during this test is provided in Figure A.8.

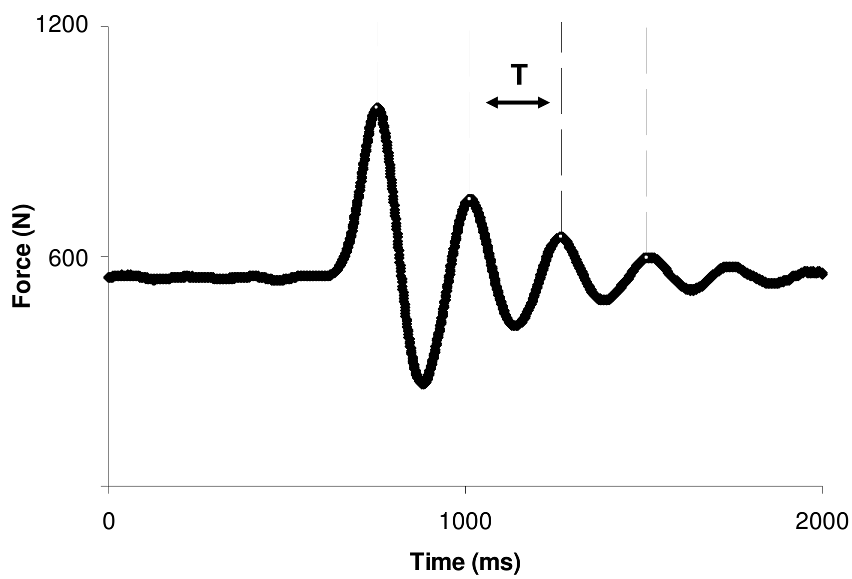


Figure A.8. A damped spring oscillation.
T Time between successive force peaks.

Based on the time between force peaks, a calculation of MTS can be performed by first determining the amount of damping that has occurred. This is revealed by the calculation:

$$\delta = ln \frac{T_2}{T_3}$$

Where:

δ - The logarithmic decrement of the oscillation waveform

ln - The natural logarithm function

T_2 - Time at 2nd force peak

T_3 - Time at 3rd force peak

This equation creates a value for the amount of damping occurring as a result of the viscoelastic properties of the musculature involved in the movement. In contrast to previous studies, which examined the time of the first and second waveform peak after perturbation (McNair *et al.*, 1992; Wilson *et al.*, 1994), the timing of the second and third peaks were analysed in the current experiment. This was performed to improve the validity of the MTS assessment, given that the time between peaks in the waveform must be identical for the equation to be valid. In this respect, pilot work revealed that the time between first and second peaks was often dramatically different (>5%) than the time between peaks two and three and peaks three and four. This may be attributed to an invoked stretch reflex response or differences in the duration of the force applied during perturbation changing the point at which external force is removed.

Once the amount of damping was determined, the damping factor was then established using the equation:

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}}$$

Where:

ζ - The damping factor

δ - The logarithmic decrement of the oscillation waveform

Once the damping factor was known, the natural frequency of oscillation was ascertained using the following equation:

$$\omega_n = \frac{\omega_d}{\sqrt{1 - \zeta^2}}$$

Where:

ω_n - The natural frequency of oscillation (oscillations/second)

ω_d - The damped frequency of oscillation (oscillations/second)

ζ - The damping factor

The co-efficient of damping was then calculated using the following equation:

$$c = 2m\zeta\omega_n$$

Where:

c - The co-efficient of damping

m - The mass of the barbell

ζ - The damping factor

ω_n - The natural frequency of oscillation (oscillations/second)

Finally, the results these equations were then used to determine MTS using the following equation:

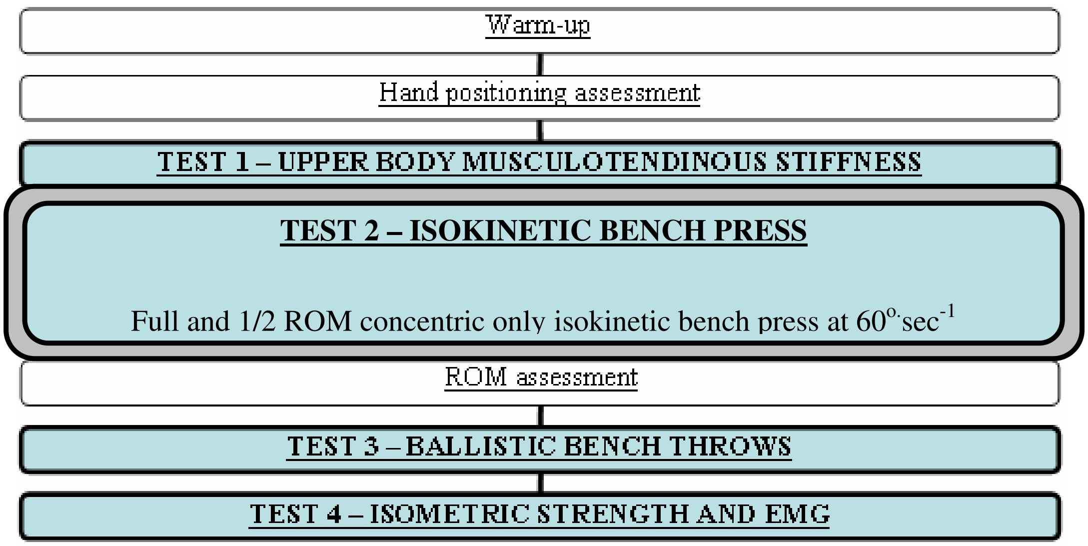
$$k = 4\pi^2 m \omega_d^2 + \frac{c^2}{4m}$$

Where:

k - Musculotendinous stiffness

m - The mass of the barbell

ω_d - The damped frequency of oscillation (oscillations/second)



Test 2 - Isokinetic concentric only bench press

To perform this test, a custom made bench press attachment was created and connected to an isokinetic dynamometer (Biodex System 3, U.S.A.). The role of the dynamometer was to control the velocity of the bench press movement and to monitor the position of the bar. The force plate mounted bench (see Figure A.7.), was used to assess vertical force. During the test, the custom made bar was loaded with a 60 kg mass to prevent Biodex malfunction. In this respect, the additional load reduced the torque applied to the motorised velocity control mechanism of the Biodex without compromising the force generation associated with the test. An example of the isokinetic bench press test is displayed in Figure A.9.

Figure A.9. The isokinetic bench press test.
These images provide the frontal (left) and side (right) views. Spotters placed their hands lightly around the bar to prevent injury to the subject in the event of an equipment malfunction.

The subjects performed four total sets of concentric only isokinetic bench press. Two sets of five repetitions were performed throughout the full ROM of the bench press movement, with another two tests performed in the terminal half of the ROM. Velocity was set at $45^{o}\cdot sec^{-1}$ for all tests, as this closely replicates the velocity of movement during heavy, free weight bench press as shown previously by Lander *et al.* (1985).

The subjects started the exercise by lying on the force plate mounted bench in a position where the bar on the Biodex attachment was directly superior to the areola, the typical bench press position at the bottom of the movement. Hand position was standardised between tests, so that it replicated the position previously mentioned in the hand positioning assessment protocol, by adjusting the handgrips. Once hand positioning was set, the following steps were carried out:

1. The subject's ROM was established. The full ROM position was set with the bar lightly touching the chest, with the terminal ROM set at complete elbow extension. This was established using the Biodex controller to ensure that the bar would be restricted to the ROM specified. The angle that the bar was moved through during a complete repetition was recorded in the subject's information sheet.
2. The bar was then returned to the chest to prepare for the start of the isokinetic tests. At this point the attachment was then loaded with an evenly distributed 60 kg mass.
3. The subject was instructed to perform five maximal, full ROM concentric only repetitions upon hearing the audible start signal. The subjects were instructed to allow the Biodex machine to lower the bar down to their chest. While the attachment was being lowered, the subjects were instructed to maintain hand contact with the bar. The full ROM isokinetic bench press movement is detailed in Figure A.10.

Figure A.10. Side view of the full ROM isokinetic bench press movement. The starting position was with the attachment lightly touching the chest (left), with the end of the movement set to full elbow extension (right).

4. Once the set of five repetitions was completed, the subject was given a one minute rest interval before performing the next test.

For the half ROM tests, the ROM was set so that the bar could only be moved throughout the terminal half of the ROM. This was established by halving the angle of the full ROM repetition, and setting the Biodex to restrict movement to this half ROM angle from full elbow extension, as described in Figure A.11. The subjects again performed two sets of five repetitions of concentric only isokinetic bench press.

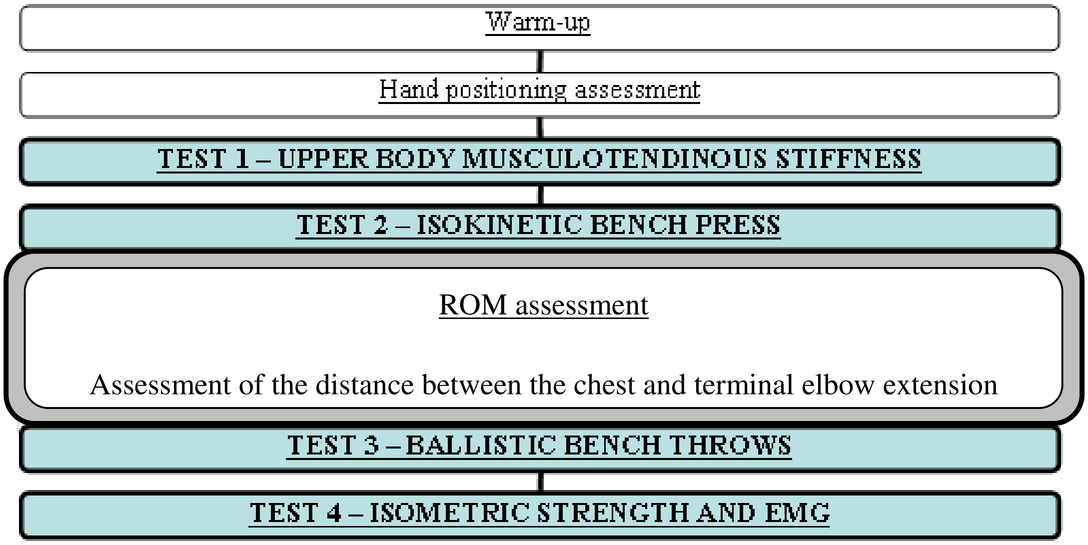
Figure A.11. Frontal view of the half ROM isokinetic bench press movement.
The starting position at the half ROM position (left) and the end of the movement at full elbow extension (right).

The position data, received from the isokinetic dynamometer, was synchronized with the force output, recorded by the force plate, using custom written Labview software and acquisition equipment (National Instruments, U.S.A.). Performing the data collection in this way was advantageous for a number of reasons. Firstly, it allowed the data from both the dynamometer and the force plate to be synchronously sampled at 1000 Hz. Secondly, the addition of the 60 kg mass to the bar, plus the fact that the test was novel to the dynamometer software, often resulted in the standard analysis software malfunctioning. The Labview software overcame this difficulty, and in addition, provided a true indication of the vertical forces applied to the bar. Furthermore, pilot testing using a position transducer (IDM Instruments, Australia) connected to the bench press attachment revealed that there was a slight (80ms) delay between actual movement of the bar and the change in positional signal received in the data acquisition software. This was corrected for during data analysis.

The custom written data acquisition and analysis package was used to determine the peak concentric force, mean concentric force and position of peak force. The mean peak concentric force produced during the three median repetitions for each set was deemed the mean peak force for that test. The mean concentric force was also an average of the three median repetitions, with the mean concentric force for these three repetitions examined. Only the concentric phase of the movement was analysed, with the phase of the movement between the initial and final positive displacement measures deemed the cut-off points.

Further analysis for the full ROM tests consisted of both peak and mean force production in each quarter of the ROM. This was necessary for the subsequent training study to determine whether the VROM intervention resulted in a change in the force/ROM curve characteristics. To perform this, the ROM curve was split into each quarter based on the positional data.

One limitation in regards to assessment of force was that the movement was not purely linear given that the lever arm was rotating about a fixed point. However, the custom made bench was setup so that the isokinetic bench press would be as vertical as mechanically possible. This resulted in the directly vertical phase of the movement occurring in the midrange of the bench press ROM. Furthermore, this curvilinear movement replicates the optimal biomechanical movement pattern during the bench press exercise (Shepard, 2004).



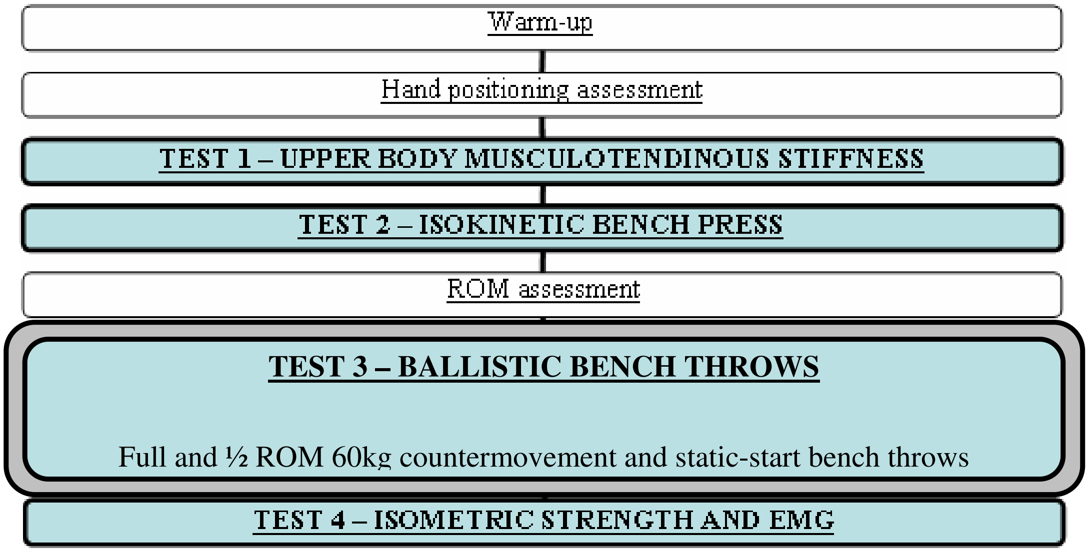
<u>ROM assessment</u>

The remaining tests were all performed using the force plate mounted weights bench, however, for these tests a Smith Machine (Calgym, Australia) was incorporated to restrict movement of the barbell to a vertical, linear plane. Displacement was measured during the remaining tests using a position transducer (IDM Instruments, Australia). Prior to the bench throws, the subject's bench press ROM was assessed with points at full, ¾, ½, ¼ and terminal ROM subsequently determined. Assessing the subject's ROM, and determining each one quarter interval, provided positions for the countermovement during the half ROM bench throws and the restraints during the isometric trials.

This test commenced with the subject lying prone on the custom weight bench in a typical bench press position, with their areola directly inferior to the Smith machine barbell. The subject then gripped the barbell in the standard bench press position with each hand placed directly outside the sliders, which were set in the same position as the sliders used during the MTS tests performed in Test 1. The ROM was assessed according to the following steps:

1. The subjects lowered the barbell to their chest, which was deemed the full ROM position. This position was set on the Labview computer as the full ROM position.
2. The subject was then instructed to raise the barbell until it was at full elbow extension. This was deemed the terminal ROM, and was set on the Labview computer as the final ROM position.

The software recorded these positions for the subject and performed two additional functions. Firstly, it was programmed to make a loud audible beep when the barbell reached the half ROM point during descent. This provided the signal for the subject to perform a countermovement during the half ROM bench throws, and also set the start point for the static-start half ROM bench throws. Secondly, it provided a real time display of the barbells positioning in the ROM relative to the end points. This allowed for accurate and simple positioning of the barbell during the isometric strength and EMG tests. Once this positional data was collected, the subject commenced the ballistic bench throw testing.



Test 3 - Ballistic Bench Throws

All ballistic force tests were performed with an absolute load of 60 kg. This load was chosen because it provided a mass that would allow the subjects to be performing near their peak power output based on their previously determined strength levels (Wilson *et al.*, 1993). To begin the bench throw testing, the subject was instructed to lie on the custom weight bench in the prone, bench press position. The subjects then gripped the barbell in their standardised hand position in preparation for performing the ballistic bench throws.

These tests consisted of a total of three sets of three repetitions, with a one minute rest between repetitions. The repetitions during each set were separated by a 15 second rest interval, both to reset the data collection software and also allow recuperation. Due to the submaximal load and single repetition performed, this time frame was deemed suitable for subject recovery. The individual sets consisted of three different throwing conditions; full ROM with a countermovement, full ROM with a static-start and half ROM with a static-start.

During the full ROM countermovement set, the 60 kg barbell was unhooked from the Smith machine and lifted to the point where the subject's elbows were fully extended at the terminal ROM. Upon instruction by the investigator, the subject performed a ballistic bench throw. This movement required the subject to lower the barbell to the chest, perform the countermovement and explosively throw the barbell into the air as high as possible. The subject was then required to catch the barbell during its descent, absorb the downward force and then return it to the initial starting position.

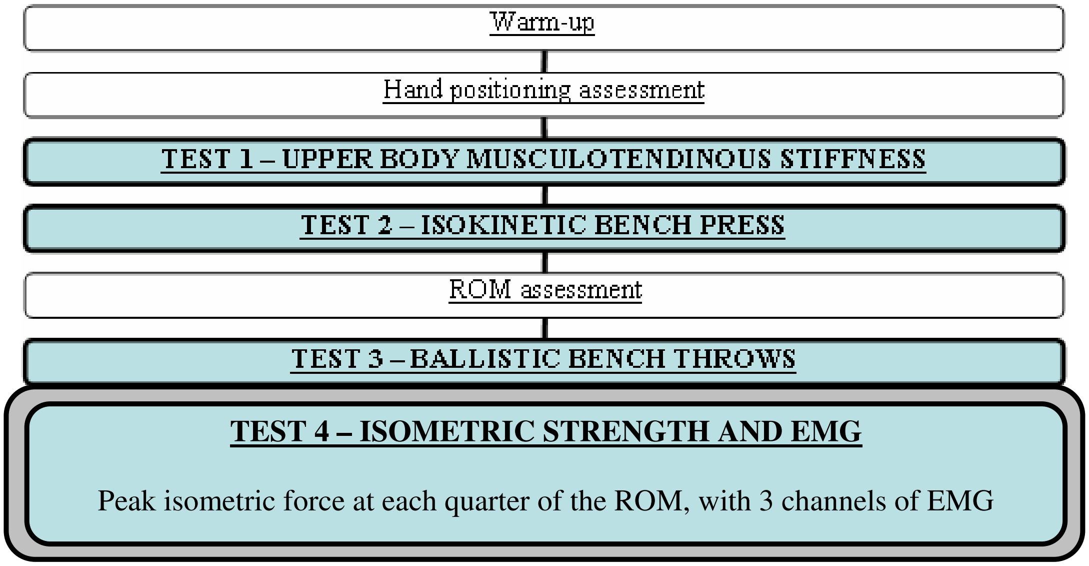
The starting position for the static-start bench throws was at the full ROM position, with the barbell lightly touching the chest. These throws were concentric only, with no countermovement performed prior to the test. The Plyopower™ (Fitness Technologies, Australia) brake was adjusted to maximal setting throughout all static-start tests, which provided a descent braking force of approximately 220 kg. This ensured that the descent of the barbell was controlled by the brake and not by the subject. This reduced the potential for elastic energy storage that would occur if the subject lowered the barbell to the starting position, or was required to isometrically hold the barbell in position. Once the barbell reached the starting position, a five second rest interval was enforced before an audible signal to perform the next repetition.

For the half ROM static-start bench throws, the Plyopower™ brake was maintained at a maximal setting, holding the barbell stationary during the barbells descent. This allowed for manual manipulation of the barbell to start the static throws from the half ROM position. To start the set, the barbell was physically lowered to the half ROM position, which was signalled by the position analysis software, by the researcher. The subject was then instructed to grip the barbell in preparation for performance of the throw. As for the previous tests, an audible signal provided by the investigator alerted the subject to perform a bench throw. The brake then halted the descent of the bar, at which point the investigator physically lowered the barbell back to the half ROM point. A five second rest interval was provided between the subject gripping the bar and performing the next throw.

Both the force plate and the position transducer were set to initiate recording data in response to a keystroke performed by the investigator. This ensured that data for the entire movement was collected. Only the positive phase of the movement was analysed, and therefore it was necessary to determine the cut-off points for the concentric data. The onset of the positive phase of the movement was deemed to have occurred at the time of the first positive displacement data point during the concentric phase of the countermovement. The terminal cut-off point was determined as the point at which the barbell left the hands, which was determined based on the terminal ROM position data recorded during the preceding ROM tests. An example of the displacement cut-off points, and the corresponding force trace, are provided in Figure A.12.

Figure A.12. The cut-off points for the ballistic bench throw force curve, based on positional data.

Peak and mean force were assessed by taking the respective force readings for the concentric ROM. From the data within these ranges, the time to peak force, peak force and mean force for each of the tests was also determined. The repetition with the greatest vertical displacement was used for data analysis.



Test 4 - Isometric Bench Press Force and EMG

To perform the final tests, the Smith machine was set-up with a custom made isometric bench press attachment. This consisted of a horizontal bar securely mounted to the base of the Smith machine. Two high tensile, braided cables were connected between the horizontal bar and the barbell. This restricted the subject from being able to lift the barbell vertically past a pre-determined position, which was based on the results of the previous bench press ROM assessment. The position was set by adjusting the length of the cables in accordance with the real time position data provided by the position transducer. Three channels of integrated surface EMG with a 10000:1 amplified gain were also used to assess muscle activation during the isometric tests (Delsys, U.S.A.).

The isometric tests were performed using a five second ramp protocol, in accordance with the following steps:

1. Preparing the EMG electrode placement sites
2. Subject positioning and zeroing the force plate
3. Placement of the electrodes

4. Setting the testing position
5. Performing the isometric test

1. Preparing the EMG electrode placement sites

The electrode placement sites were measured, marked, shaved, abraded and swabbed in the rest interval immediately after the ballistic bench throw tests. Electrode placement sites were assessed with the subject lying in the bench press position while lightly grasping the barbell, and were similar to those performed by Kelly, Backus, Warren and Williams (2002). The three sites were the:

- PECTORALIS MAJOR

  The subjects were instructed to stand in the anatomical position facing the investigator. The electrode placement site was located directly superior to the nipple and directed along a line halfway between the most superior aspect of the axillary fold (located by site) and the attachment of the xiphoid process to the sternum (located by palpation).

- ANTERIOR DELTOID

  This electrode placement site was located halfway between the most superior aspect of the axillary fold (located by site) and the most superior aspect of the acromioclavicular joint (located by palpation). Once the position was marked, the subject was instructed to abduct and externally rotate their arm into a "bicep flexion pose" position, with their upper arm parallel to the ground. The investigator then manually palpated the marked position to ensure it was directly over the belly of the anterior deltoid. The position of the electrodes for both the pectoralis major and anterior deltoid are provided in Figure A.13.

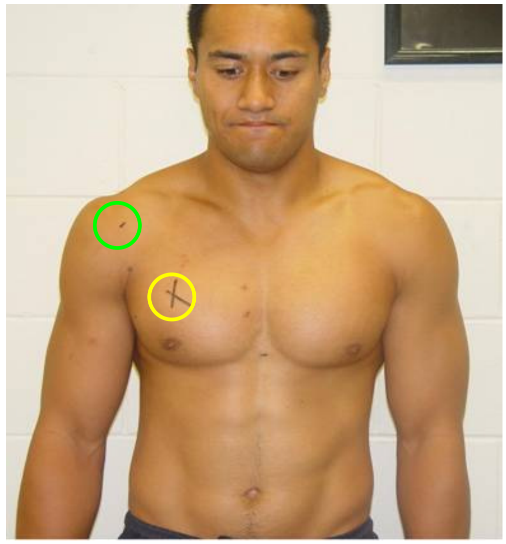


Figure A.13. The EMG electrode position for the isometric strength tests.
○ pectoralis major (yellow)
○ anterior deltoid (green)

- LONG HEAD OF THE TRICEPS BRACHII

This electrode placement site replicated the site where the ULT scan was performed (see Section A.2.2). This allowed for potential architectural changes in the muscle at that site detected by the ULT scans to be compared with any subsequent changes in electrical activity of the muscles.

A reference electrode was also placed on the olecranon process of the right arm. This site was determined by manually locating the bony protrusion on the elbow and shaving, abrading and swabbing the site with alcohol.

2. Subject positioning and zeroing the force plate

Once the subject was marked for electrode placement sites, they were instructed to lie on the custom weights bench in the standardised bench press position.

The subject was instructed to assume the lifting position but not to actually touch the barbell, at which point the force plate was zeroed.

3. Placement of the electrodes

The subject was then instructed to grip the barbell as if preparing for a lift. At this point the electrode placement sites were verified to ensure that the position was running parallel with the muscle fascicles over the belly of the respective muscle. Electromyographic activity of the three muscles was detected using 99.9% silver pre-amplified surface electrodes (Delsys, U.S.A). These electrodes were bipolar, with a single differential, parallel bar electrode configuration consisting of an inter-electrode distance of 10 mm. Prior to placement of the electrodes, the sites were shaved with a razor, abraded with sandpaper and swabbed with alcohol. This assisted in optimising the conduction of the electrodes, which were then placed on their respective sites and secured to the skin using the supplied interface (Delsys, U.S.A). Surgical tape (Micropore, China) placed over the electrodes was also used to prevent unwanted movement and electrical interference. If excessive noise was present in the EMG signal, the electrode was removed and the entire process was repeated.

4. Setting the testing position

The isometric testing positions were based on the distance between terminal and full bench press ROM measured during the ROM assessment test. From this full ROM result the movement was split into equal displacement quarters, with an isometric test performed at each of the ¼, ½, ¾ and full ROM positions respectively. The real-time position analysis program provided the position in the ROM where each test was to be performed.

5. Performing the isometric test

Once these tests were complete, the subject was now ready to commence the isometric strength tests. Isometric contractions were held at each position for five seconds using a ramp protocol, with a one minute rest between tests. The subject was instructed to gradually increase force production for the first two seconds of the test. An audible cue at the start, and one second after commencement of the test, alerted the subject to steadily increase force. Another audible cue two seconds after beginning the test signalled the subject to produce peak force until the cessation of the test. These audible cues were provided by the position analysis software package.

All analysis of force and EMG data was performed using a custom written LabView software program (National Instruments, Texas). The peak force generated in the z-axis was assessed, with force measured throughout the duration of the test. The onset of force data collection was also synchronized with the EMG by the acquisition software.

For analysis of EMG, the data corresponding to the median 1.024 second interval occurring during the three second MVC was separated from the EMG data array. Analysis of this one second interval of EMG data consisted of median power frequency (MPF), measured in the frequency domain, and the mean root-mean-square amplitude (RMS), measured in the time domain. Consequently, because of the need to examine the data in both the frequency and time domains, the raw EMG data was filtered using two different, totally independent methods to enhance the accuracy of the results. The two filtering techniques and the subsequent analysis are described in the flowchart depicted in Figure A.14.

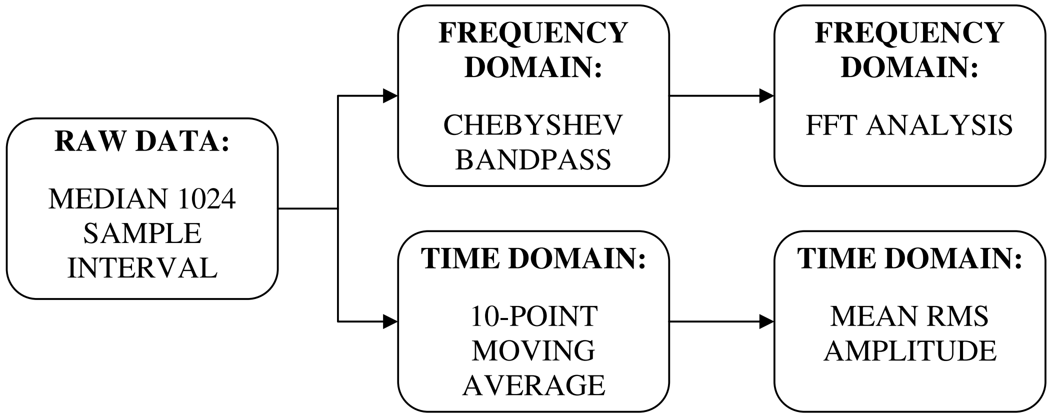


Figure A.14. Flowchart of the analysis of EMG data in the frequency and time domains.

Firstly, for the Fast Fourier Transformation (FFT) analysis, a bandpass filter was applied to the raw data. This filter consisted of dual Chebyshev filters, with cut-off frequency thresholds of 10 Hz and 450 Hz for the high and low pass filters respectively. This allowed for a reduction in noise whilst still respecting the FFT laws (Smith, 1997). Eight pole Chebysehv filters were utilized because of their enhanced roll-off response in comparison with the more commonly used Butterworth style filter (Smith, 1997). Passband ripple was set at 0.5% in an effort to reach an optimal compromise between passband ripple and the roll-off characteristics of the filter (Smith, 1997). Once the data was filtered, it was ready for the FFT analysis to be performed. This consisted of an FFT power spectral density transformation of the data, performed using a Hamming window, with a resulting frequency bin resolution of approximately 0.98 Hz. The MPF was then assessed by determining the frequency bin in which the median power spectral density value was located.

Secondly, for the RMS analysis, a 10 point moving average was performed on the raw data. Whilst this process of filtering the data is rudimentary, it is still regarded as one of the most accurate methods of filtering data in the time domain (Smith, 1997). Once the data was filtered, it was then converted into RMS values by finding the square root of each value in the EMG arrays square. This resulted in all EMG data becoming positive values, and allowed for the mean amplitude of the 1024 ms interval to be determined by averaging the data in the array.

The EMG amplitude data for the ¼, ½ and ¾ ROM tests were normalised to the results in the full ROM position. Normalising EMG data this way allowed for determination of changes in ROM specific activation properties (De Luca, 1997).

A.2.5 Statistical Analysis

Each test was performed twice to allow for inter-test reliability assessment. This was performed by determining the intraclass correlation coefficient (ICC) and standard error of the measurement (SEM) values for each test. ICC values (R) were obtained by performance of reliability analysis using within subjects ICC statistical analysis (SPSS Version 14.0). SEM, which is used for assessing the results of a single testing session, was determined using the following calculation:

$$SEM = STDEV*(\sqrt{(1-ICC)})$$

Where STDEV represents the standard deviation of the values. This measurement is applicable to Experiment 2.

Typical error of the difference (TE), which provides information about the expected variability between testing sessions (Hopkins, 2000), was determined using the equation:

$$TE = SEM * \sqrt{2}$$

This measurement is applicable to Experiment 3, in which two separate sessions were performed. Any test which reported an ICC value of less than R=0.80, which is considered the cut-off threshold for moderate reliability (Vincent, 1995) was reviewed. These tests were then excluded from the remaining studies by the primary investigator if it was believed that the test could not be improved to ensure reliable assessment of the measured variable.

A.3 RESULTS

The results for each test are presented in the order that the tests were explained in the methodology section. These results are provided in the following tables, with a discussion focussing on the suitability for inclusion during the training study provided before each table.

The results of Table A.1 show that the only muscle architecture measure with an ICC value of less than R=0.80 was the distal medial head pennation angle (R=0.75), which in turn effected the ICC value for the corrected distal medial head angle (R=0.74). Overall the muscle architecture measurements were highly repeatable and were therefore included in the training study.

Table A.1. Reliability of architectural measures of the long and medial heads of the triceps brachii.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
Distal long head pennation angle (^{o})				
9.6 ± 1.8	10.0 ± 1.7	0.87	0.84	1.19
Proximal long head pennation angle (^{o})				
10.6 ± 3.0	10.8 ± 2.6	0.86	1.13	1.59
Distal medial head pennation angle (^{o})				
8.1 ± 1.4	8.2 ± 1.3	0.75	0.69	0.97
Proximal medial head pennation angle (^{o})				
8.2 ± 2.0	8.6 ± 2.4	0.91	0.62	0.88
Distal long head muscle thickness (cm)				
0.8 ± 0.3	0.8 ± 0.3	0.95	0.08	0.11
Proximal long head muscle thickness (cm)				
0.8 ± 0.3	0.8 ± 0.3	0.95	0.06	0.08
Distal medial head muscle thickness (cm)				
1.5 ± 0.3	1.5 ± 0.3	0.94	0.08	0.11
Proximal medial head muscle thickness (cm)				
1.4 ± 0.3	1.4 ± 0.3	0.91	0.09	0.13
Distal long head corrected angle ($^{o}\cdot cm^{-1}$)				
13.8 ± 6.1	0.8 ± 0.3	0.84	2.42	3.42
Proximal long head corrected angle ($^{o}\cdot cm^{-1}$)				
15.0 ± 6.0	0.8 ± 0.3	0.86	2.23	3.15
Distal medial head corrected angle ($^{o}\cdot cm^{-1}$)				
5.6 ± 1.3	5.6 ± 1.0	0.74	0.65	0.92
Proximal medial head corrected angle ($^{o}\cdot cm^{-1}$)				
6.2 ± 2.0	6.4 ± 2.0	0.95	0.44	0.62

Table A.2 outlines that the majority of the isokinetic performance measures were highly reliable. However, both third quarter mean force (R=0.77) and time to first peak (R=0.65) produced ICC values less than R=0.80. The relatively poor ICC value for the time to first peak lead to its exclusion from the data analysis performed during the training study.

Table A.2. Reliability of isokinetic full ROM bench press.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
Peak force (N)				
1279 ± 223	1237 ± 246	0.88	77.90	109.95
1st quarter peak force (N)				
1037 ± 268	1049 ± 319	0.94	65.97	93.11
2nd quarter peak force (N)				
1104 ± 194	1045 ± 177	0.88	66.52	93.89
3rd quarter peak force (N)				
1236 ± 234	1191 ± 224	0.87	84.11	118.71
4th quarter peak force (N)				
958 ± 138	923 ± 176	0.90	43.88	61.93
Mean force (N)				
924 ± 139	874 ± 158	0.85	53.33	75.27
1st quarter mean force (N)				
864 ± 161	847 ± 225	0.99	19.38	27.35
2nd quarter mean force (N)				
863 ± 126	816 ± 153	0.92	36.36	51.32
3rd quarter mean force (N)				
1009 ± 139	953 ± 153	0.77	66.59	93.99
4th quarter mean force (N)				
1096 ± 177	1077 ± 213	0.81	76.70	108.26
Time to 1st force peak (ms)				
60 ± 29	51 ± 30	0.65	31.42	44.35
Time to 2nd force peak (ms)				
721 ± 53	765 ± 54	0.86	10.80	15.24

The results of Table A.3 show that the isokinetic half ROM tests recorded very high repeatability, with only the third quarter mean force (R=0.84) producing an ICC of R<0.90.

Table A.3. Reliability of isokinetic half ROM bench press.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
Peak force (N)				
1507 ± 305	1484 ± 312	0.92	84.25	118.91
3rd quarter peak force (N)				
1199 ± 228	1251 ± 276	0.90	70.79	99.91
4th quarter peak force (N)				
1504 ± 308	1480 ± 310	0.92	87.64	123.70
Mean force (N)				
1114 ± 158	1122 ± 196	0.90	49.28	69.55
3rd quarter mean force (N)				
908 ± 157	925 ± 173	0.84	62.85	88.71
4th quarter mean force (N)				
1321 ± 246	1320 ± 275	0.90	76.03	107.31
Time to 1st force peak (ms)				
372 ± 86	383 ± 68	0.91	26.28	37.09

The results of Table A.4 shows that the majority of variables associated with the ballistic bench throws were highly repeatable, with an ICC value of R>0.80. However, mean force during the half ROM static throws (R=0.73) produced an ICC value of R<0.80. Furthermore, the half ROM static throw TTP produced highly variable results, as reflected in its ICC value of only R=0.41. Therefore, these measures were excluded from the study.

Table A.4. Reliability of 60kg bench throws.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
Full ROM countermovement throw - displacement (cm)				
14.7 ± 4.2	14.4 ± 3.9	0.95	0.94	1.33
Full ROM static throw - displacement (cm)				
12.3 ± 3.9	12.94 ± 4.26	0.88	1.35	1.91
Half ROM static throw - displacement (cm)				
13.5 ± 3.2	14.34 ± 3.34	0.87	1.14	1.61
Full ROM countermovement throw - peak force (N)				
1504 ± 316	1562 ± 319	0.83	129.84	183.26
Full ROM static throw - peak force (N)				
1185 ± 151	1204 ± 186	0.93	39.5	55.75
Half ROM static throw - peak force (N)				
1421 ± 226	1406 ± 237	0.87	83.77	118.23
Full ROM countermovement throw - mean force (N)				
962 ± 109	950 ± 101	0.96	23.04	32.52
Full ROM static throw - mean force (N)				
932 ± 129	926 ± 124	0.99	9.16	12.93
Half ROM static throw - mean force (N)				
845 ± 106	803 ± 99	0.73	55.15	77.84
Full ROM static throw - time to peak (ms)				
481 ± 218	446 ± 201	0.96	43.58	61.51
Half ROM static throw - time to peak (ms)				
322 ± 164	279 ± 91	0.41	125.64	177.33

The results of Table A.5 show that of all the performance measures, the isometric bench press recorded the highest variability between trials. Both the one quarter (R=0.77) and half ROM (R=0.72) tests produced ICC values of R<0.80. However, the results for the three quarter ROM test and the test performed on the chest were highly repeatable.

Table A.5. Reliability of isometric force measures.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
¼ ROM isometric peak force (N)				
1800 ± 411	2000 ± 297	0.77	197.12	278.22
½ ROM isometric peak force (N)				
1574 ± 206	1708 ± 254	0.72	108.47	153.10
¾ ROM isometric peak force (N)				
1340 ± 187	1358 ± 223	0.90	59.53	84.02
Chest isometric peak force (N)				
1310 ± 189	1562 ± 175	0.83	78.60	110.94

The results of Table A.6 show that EMG mean amplitude proved to be highly unreliable, with the majority of tests receiving ICC values of R<0.80. None of the measurements for the anterior deltoids were even close to reliable, therefore anterior deltoid amplitude EMG was excluded from the data analysis during the training study. The only amplitude measures with an ICC value of R>0.80 were the isometric test with the bar on the chest (pectoralis major R=0.99, triceps long head R=0.80) and the normalised amplitude during the one quarter ROM test (pectoralis major R=0.83, triceps long head R=0.83). Therefore, only these EMG amplitude measures were examined during the training study.

Table A.6. Reliability of normalised amplitude EMG analysis during isometric bench press tests.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
¼ ROM – pectoralis major normalised amplitude (%)				
151.23 ± 53.23	146.15 ± 60.40	0.83	21.87	30.87
¼ ROM – anterior deltoid normalised amplitude (%)				
168.21 ± 72.85	176.93 ± 50.25	0.57	47.54	67.10
¼ ROM – triceps brachii normalised amplitude (%)				
171.72 ± 79.92	185.27 ± 79.86	0.83	33.03	46.62
½ ROM – pectoralis major normalised amplitude (%)				
108.82 ± 44.80	115.25 ± 38.51	0.39	34.97	49.36
½ ROM – anterior deltoid normalised amplitude (%)				
96.72 ± 44.19	124.03 ± 48.69	0.44	33.04	46.63
½ ROM – triceps brachii normalised amplitude (%)				
96.65 ± 53.48	111.73 ± 41.56	0.37	42.45	59.91
¾ ROM – pectoralis major normalised amplitude (%)				
170.91 ± 62.56	166.14 ± 64.53	0.31	71.73	101.24
¾ ROM – anterior deltoid normalised amplitude (%)				
225.38 ± 129.83	250.87 ± 123.71	0.20	142.68	201.38
¾ ROM – triceps brachii normalised amplitude (%)				
179.80 ± 80.35	214.79 ± 102.76	0.10	84.16	118.79
Chest – pectoralis major amplitude (µV)				
0.0266 ± 0.0154	0.0314 ± 0.0192	0.99	0.00	0.00
Chest – anterior deltoid amplitude (µV)				
0.1026 ± 0.0702	0.0946 ± 0.0452	0.00	0.07	0.10
Chest – triceps brachii amplitude (µV)				
0.0340 ± 0.0223	0.0347 ± 0.0240	0.80	0.01	0.01

The results of Table A.7 reveal that no measurements of EMG MPF received ICC values of R>0.80. Therefore, no measurements of MPF were included in the training study.

Table A.7. Reliability of mean power frequency EMG analysis during

isometric bench press tests.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
¼ ROM – pectoralis major mean power frequency (Hz)				
59.70 ± 13.72	68.75 ± 16.47	0.4	10.22	14.42
¼ ROM – anterior deltoid mean power frequency (Hz)				
75.73 ± 12.13	101.31 ± 34.56	0.36	11.51	16.25
¼ ROM – triceps brachii mean power frequency (Hz)				
83.22 ± 16.96	89.55 ± 32.93	0.41	8.21	11.59
½ ROM – pectoralis major mean power frequency (Hz)				
56.54 ± 13.58	61.51 ± 15.62	0.32	14.01	19.77
½ ROM – anterior deltoid mean power frequency (Hz)				
70.15 ± 20.77	94.98 ± 28.27	0.01	12.81	18.08
½ ROM – triceps brachii mean power frequency (Hz)				
90.11 ± 20.03	102.59 ± 21.63	0.58	12.25	17.29
¾ ROM – pectoralis major mean power frequency (Hz)				
49.75 ± 9.70	62.83 ± 12.00	0.21	12.11	17.09
¾ ROM – anterior deltoid mean power frequency (Hz)				
74.63 ± 13.87	101.28 ± 42.08	0.21	10.13	14.30
¾ ROM – triceps brachii mean power frequency (Hz)				
81.09 ± 16.59	96.76 ± 26.48	0.78	8.25	11.64
Chest – pectoralis major mean power frequency (Hz)				
60.61 ± 17.35	66.94 ± 13.96	0.63	13.82	19.51
Chest – anterior deltoid mean power frequency (Hz)				
74.13 ± 10.86	90.96 ± 22.03	0.33	19.4	27.38
Chest – triceps brachii mean power frequency (Hz)				
77.94 ± 19.90	85.78 ± 21.52	0.58	11.69	16.5

The results of Table A.8 shows that the median two results for the MTS test proved to be highly reliable (R=0.92).

Table A.8. Reliability of upper body musculotendinous stiffness.

TRIAL 1	TRIAL 2	ICC (R)	SEM (±)	TE (±)
Musculotendinous stiffness ($N \cdot m^{-1}$)				
19918 ± 8515	19157 ± 7897	0.92	2393.00	3377.53

A.4 DISCUSSION

The majority of tests performed in this reliability study produced ICC values greater than R=0.80. However, two of the four isometric force tests, along with the majority of EMG measures, produced unreliable results (R<0.80). Potential reasons why these tests may not have been reliable during this study will be examined in the following paragraphs.

Firstly, in regards to the isometric tests, the unfamiliarity of the subjects with maximal voluntary isometric contractions may have resulted in the sub-par reliability results. However, although the results for the two midrange tests did not reach an ICC level of R>0.80, these two results did exceed R>0.70. Therefore, these two tests were included into the training studies examination protocol, with each subject being allowed a familiarisation trial prior to testing to overcome the novel aspect of the examination.

Secondly, in regards to the poor reliability of the EMG during the majority of tests, the limitations of surface EMG have been explained in detail in numerous prior studies (De Luca, 1997; Schultz and Perrin, 1999). Although the results for MPF EMG were highly unreliable, normalised amplitude measures for the pectoralis major and long head of the triceps brachii during the one quarter and full ROM tests proved to be reliable. Therefore, these two measures were deemed acceptable for the training study.

A.5 CONCLUSION

This study allowed for the determination of reliable tests that could be included in the training study. However, not all of the reliable tests could be included in the subsequent studies, due to the large number of variables potentially increasing the risk of committing a Type II statistical error. Therefore, only the tests deemed most valid to proposed outcome measures were implemented in the training study.

Appendix B

CALCULATION OF FORCE PRODUCTION IN THE IDEALISED MODEL OF MUSCLE ARCHITECTURE

Although by no means flawless, the creation of an idealized model of muscle architecture provides an insight into the potential effects of muscle architecture on performance. For the idealized model created in Experiment 2, a number of assumptions and limitations are present. These include:

1. That fascicle force production is linearly related to fascicle length.
2. That all fascicles in the muscle group are identical in length and width.
3. No interdigitisation of force transfer between fascicles.
4. No curvature of the fascicles.
5. All fascicles insert at the same pennation angle.
6. The muscle has a cylindrical circumference.
7. The tendon/aponeurosis attachment is the same width along its entire length, and also runs centrally to the muscle group.
8. The tendon does not stretch.
9. All changes in the variables are spread evenly throughout the muscle group.
10. Total muscle volume is directly relative to PCSA.
11. This model does not account for the fascicles that do not attach to the external aponeuroses.
12. The values for pennation angle and muscle thickness are representative of the muscle at peak force production. Although this is not the case, due to the established changes in pennation angle and muscle thickness that occur during

contraction (Reeves and Narici, 2003), it is difficult to interpolate the result of a contraction on these variables.

Once these limitations were established, the idealized model was created. The focus of this model was on the two architectural features examined in Experiment 2, pennation angle and muscle thickness. Therefore, equations were created to determine the effect of a change in each of these variables on torque production.

Pennation Angle

To assess the effect of pennation angle with no effect on muscle thickness the following steps were performed:

1. Values representing $\pm$10% of the mean pennation angle were derived. This resulted in pennation angles of 12.4^{o}, 13.6^{o} and 11.2^{o} for the mean, +10% and -10% values respectively.

2. Due to the maintenance of muscle thickness, the subsequent fascicle length for each pennation angle were determined according to the equation -

$$FL = \frac{MT}{\sin PA}$$

Where FL = Fascicle Length (cm), MT = Muscle Thickness (cm) and PA = Pennation Angle (^{o}). This resulted in fascicle lengths of 5.59cm, 5.10cm and 6.18cm for the mean, +10% and -10% values respectively.

3. Once these values were established, an estimation of PCSA was performed. Based on the definition of PCSA being "the magnitude of muscle fibre area perpendicular to the longitudinal axis of individual muscle fibres multiplied by

the cosine of the angle of pennation" (Aagard *et al.*, 2001), and due to the shape of the muscle, the PCSA would consist of a conal shape running perpendicular to the muscle fascicles, and would therefore not be best represented by the equation PCSA = (Muscle volume / FL) * cos PA, which has been used in previous research (Kawakami *et al.*, 1993; Wickiewicz *et al.*, 1983). Therefore, PCSA prior to correction for mechanical efficiency, which is performed in the next step, was calculated using the equation for determining the external surface area of a cone minus the base, represented by the equation -

$$PCSA = (\pi * MT * FL)$$

This resulted in a PCSA of 21.07 cm^2, 19.23 cm^2 and 23.30 cm^2 for the mean, +10% and -10% values respectively.

4. Before force transfer to the tendon could be calculated, both the mechanical efficiency of force transfer and a correction for force changes due to fascicle length were performed. Firstly, mechanical efficiency was calculated using the equation –

$$ME = \frac{\left(\frac{MT}{\tan PA}\right)}{FL} * 100$$

Where ME = Mechanical Efficiency (%). This resulted in a mechanical efficiency of 97.64%, 97.26% and 98.07% for the mean, +10% and -10% values respectively. This equation was chosen over the more common equation for predicting mechanical efficiency, which is the cosine of the fascicle length, because the results of the cosine equation did not satisfy the Pythagoras theorem of $A^2 = B^2 + C^2$. This was due to the estimation of the length of the adjacent side of the theoretical triangle being calculated based on the estimation of the fascicle length, thereby neglecting first principles, which is a flaw inherent in previous studies (Kawakami *et al.*, 1993).

Secondly, a correction for force change due to fascicle length required the force per cm^2 of PCSA, which for this model was set at $35.0 N^{\cdot}cm^2$, to be adjusted based on the percentage change in fascicle length. Therefore, the PCSA force was multiplied by the percentage difference in fascicle length. This resulted in PCSA force values of $35.0\ N^{\cdot}cm^2$, $31.9\ N^{\cdot}cm^2$ and $38.7\ N^{\cdot}cm^2$ for the mean, +10% and -10% values respectively.

5. Once these variables were produced, the equation for force transfer to the tendon was performed using the equation –

$$FT = PCSAF * ME$$

Where FT = Force Transfer (N) and PCSAF = Physiological Cross-Sectional Area Force ($N^{\cdot}cm^2$). This resulted in a force transfer of 720.2 N, 597.1 N and 884.1 N for the mean, +10% and -10% values respectively.

6. Finally, the equation for torque about the joint axis for each variation of the muscle group was calculated based on the equation –

$$T = FT * D$$

Where T = Torque ($N^{\cdot}m$) and D = Displacement from insertion to the joint axis of rotation (m), which for this model was set at 0.023 m. This resulted in a torque of 16.57 N, 13.73 N and 20.33 N for the mean, +10% and -10% values respectively. These results corresponded to a torque production percentage difference of -17.1% and +22.7% for the +10% and -10% changes in pennation angle respectively.

Muscle Thickness

The equations performed to determine the effect of muscle thickness on torque production were identical to those used for assessment of pennation angle.

1. Firstly, values representing ±10% of the mean muscle thickness were derived. This resulted in muscle thicknesses of 1.20 cm, 1.32 cm and 1.08 cm for the mean, +10% and -10% values respectively.

2. Due to the maintenance of pennation angle, the subsequent fascicle length for each muscle thickness value was determined based on the equation used in Step 2 of the determination of the effect of pennation angle. This resulted in fascicle lengths of 5.59 cm, 6.15 cm and 5.03 cm for the mean, +10% and -10% values respectively.

3. An estimation of PCSA was then performed based on the equation used in Step 3 of the determination of the effect of pennation angle. This resulted in a PCSA of 21.07 cm^2, 25.50 cm^2 and 17.07 cm^2 for the mean, +10% and -10% values respectively.

4. Due to no changes in pennation angle, mechanical efficiency was 97.64% for each value of muscle thickness. Using the equation in Step 4 of the determination of the effect of pennation angle, the results for PCSA force

values were 35.0 N·cm^2, 38.5 N·cm^2 and 31.5 N·cm^2 for the mean, +10% and -10% values respectively.

5. Using the force transfer equation from Step 5 of the determination of the effect of pennation angle, a force transfer of 720.2 N, 958.8 N and 524.8 N for the mean, +10% and -10% values respectively was determined.

6. Finally, using the equation for torque about the joint axis from Step 6 of the determination of the effect of pennation angle, the derived torque was 16.57 N, 22.05 N and 12.07 N for the mean, +10% and -10% values respectively. These results corresponded to a torque production percentage difference of +33.1% and -27.2% for the +10% and -10% change in muscle thickness respectively.

Change in Muscle Thickness and Pennation Angle

This value represents the effect of a change in pennation angle, and subsequent muscle thickness, if fascicle length is maintained.

1. Firstly, based on the $\pm$10% change in pennation angle, values for the change in muscle thickness were derived using the equation –

$$MT = FL * \sin PA$$

This resulted in muscle thicknesses of 1.20 cm, 1.31 cm and 1.09 cm for the mean, +10% and -10% values respectively.

2. An estimation of PCSA was then performed based on the equation used in Step 3 of the determination of the effect of pennation angle. This resulted in a

PCSA of 21.07 cm^2, 23.01 cm^2 and 19.14 cm^2 for the mean, +10% and -10% values respectively.

3. Mechanical efficiency was identical to the results from Step 4 of the determination of the effect of pennation angle, which were 97.64%, 97.26% and 98.07% for the mean, +10% and -10% values respectively. Due to the maintenance of fascicle length, no correction of PCSA force values was necessary.

4. Using the force transfer equation from Step 5 of the determination of the effect of pennation angle resulted in a force transfer of 720.2 N, 783.1 N and 657.0 N for the mean, +10% and -10% values respectively.

5. Finally, using the equation for torque about the joint axis for Step 6 of the determination of the effect of pennation angle, the derived torque was 16.57 N, 18.01 N and 15.11 N for the mean, +10% and -10% values respectively. These results corresponded to a torque production percentage difference of +8.7% and -8.8% for the +10% and -10% change in muscle thickness respectively.

Appendix C

DETERMINATION OF STATISTICAL POWER

Although the sample size used in a scientific study should be determined based on statistical power, the use of specialist subject populations may restrict the ability to increase subject numbers as a means of enhancing this factor. For the training study included in this thesis, the subjects were required to:

1. Possess extensive resistance training backgrounds
2. Perform an investigator supervised, identical concentric workload controlled 12 week training program preceding the intervention
3. Perform multiple strength tests in the 12 weeks leading up to the intervention
4. Be performing similar extraneous physical activity throughout the duration of the intervention.

Therefore, based on these limitations the subjects were all recruited from the same professional rugby league side. Of the 40 members of the squad, only 22 both met the selection criteria and volunteered to participate in the training study. Due to this limitation on subject numbers, it was necessary to determine the statistical power of a potential training study using this subject pool.

However, determining this statistical power was difficult due to the novelty of the training intervention. Although the training studies by Massey *et al.* (2004; 2005) included free weight partial ROM bench press training, the numerous methodological flaws of these studies, described in Section 2.5.1, excluded the use of their results. Once these studies were eliminated, the two studies deemed most suitable for use in the power equation were:

1. Specificity of limited range of motion variable resistance training (Graves *et al.*, 1989), which is described in Section 2.4.1.
2. Functional isometric training: its effects on the development of muscular function and the endocrine system over an 8-week training period (Giorgi *et al.*, 1998), which is described in Section 2.2.1.

The results of these studies allowed for an estimation of the statistical power of a VROM resistance training experiment, with 11 subjects in each of the experimental and control groups. For the following power equations the alpha level was set at p=0.05, using the equation provided in Figure C.1:

$$Z_\beta = \left[\sqrt{\frac{N * \Delta^2}{2 * Stdev^2}} \right] - Z\alpha$$

Figure C.1. Statistical power equation.
Where:
Z_β This provides the distance from the experimental mean to the alpha point, in standard deviations.
N Number of subjects (the proposed number in the present study = 11)
Δ Change in values
Zα The alpha point in standard deviations (for $p<0.05$ = 1.96)
Once Z_β is determined it is converted to a percentile based on the 'Area Under the Normal Curve' table provided by Vincent (1995). This percentile is then added to the remaining percentage of the curve (if the alpha point is to the left of the mean = +50%) to provide the statistical power value.

The results of the power equations for each of the two previously mentioned studies, if they incorporated 11 subjects per group, are provided in Table C.1.

Table C.1. Statistical power based on previous studies.
These calculations incorporate the proposed number of subjects in the present study.

STUDY	CONTROL Between Trials	EXP Between Trials	Between GROUPS - Post
Graves *et al.* (1989)	74%	100%	76%
Giorgi *et al.* (1998)	95%	64%	100%
MEAN	84.5%	82%	88%

The results of the power calculations show that, if a similar magnitude of results were found, the use of 11 subjects per group in the present study would allow for a high level of statistical power (mean P>0.80) in regards to dynamic strength performance. This suggests that the proposed training study would adequately remove the risk of committing a Type II error.

One limitations in using these two studies for determining statistical power was that they both contained training interventions of a longer duration than the one performed in this thesis (eight and ten weeks for the Giorgi *et al.* (1998) and Graves *et al.* (1989) studies respectively). This would suggest that they possessed a greater potential for any disparity in adaptations as a response to the training intervention to be revealed, therefore increasing the potential effect size.

However, the subjects in these studies had either no prior training experience (Graves *et al.*, 1989) or dramatically lower strength levels (Giorgi *et al.*, 1998) than the proposed subjects for this investigation. This would suggest that these subjects would be more likely to report increased performance levels, regardless of the training intervention, in comparison with the proposed subjects in the present study. Consequently, although the training intervention used in this study was of a shorter duration than the previously mentioned studies, the subject's extensive training history, high strength levels and the steps taken by the investigators to ensure homogenous groups, enhanced the statistical power of this examination.

Appendix D

TRAINING PROGRAMS

The training programs outlined in this appendix were performed in conjunction with the subject's field based rugby league training commitments. An example of a training week occurring during the pre-season is provided in Figure D.1.

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY	SATURDAY	SUNDAY
AM	**Gym** - Upper Body Weights	**Gym** - Fat and Fitness Club: Boxing and Cycling	**REST**	**Gym** - Fat and Fitness Club: Rowing and Cycling	**REST**	**Aerobic Fitness** - Beach runs, hill sprints etc.	**REST**
PM	**Field** (5:30pm) - 30 mins each of: SAQ training Running Fitness Games Fitness	**Gym** - Lower Body Weights + Pool Footy	**REST**	**Field** (5pm) - 30 mins SAQ training Skills and Drills Training	**Gym** - Full Body Weights + 3*500m maximal rowing	**REST**	**REST**

Figure D.1. An example of the training commitments of the subjects during the initial phase of the preseason.

Each microcycles training program, which consisted of multiple sheets, is provided in chronological order. All subjects completed the first two microcycles using an identical training program, which are provided in Figures D.2 and D.3. The training intervention was implemented during the third microcycle, with the full ROM program shown in Figure D.4 and the variable ROM (VROM) groups program provided in Figure D.5.

NAME:																		
MONDAY	**WEEK 1**			**WEEK 2**			**WEEK 3**			**WEEK 4**			**WEEK 5**			**WEEK 6**		
	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM
BALL BAG CIRCUIT																		
Bench Press WU		10			10			8			8			6			6	
Bench Press 2		10			10			8			8			6			6	
Push-up jump 1		8			8			10			10			12			12	
Push-up jump 2		8			8			10			10			12			12	
Bench Press 3																		
Seated Row WU		10			10			8			8			6			6	
Seated Row 2		10			10			8			8			6			6	
Dumbell lawnmowers 1		8			8			10			10			12			12	
Dumbell lawnmowers 2		8			8			10			10			12			12	
Seated Row 3																		
Incline Bench Press WU		10			10			8			8			6			6	
Incline Bench Press 2		10			10			8			8			6			6	
Shrugs 1		8			8			10			10			12			12	
Shrugs 2		8			8			10			10			12			12	
Incline Bench Press 3																		
Rack Clean WU		10			10			8			8			6			6	
Rack Clean 2		10			10			8			8			6			6	
Cable Bag Throwdown 1		8			8			10			10			12			12	
Cable Bag Throwdown 2		8			8			10			10			12			12	
Rack Clean 3																		
Wtd Ab Crunch 1		15			15			20			20			25			25	
Wtd Ab Crunch 2		15			15			20			20			25			25	
Forearm Bridge 1		12			12			12			12			12			12	
Forearm Bridge 2		12			12			12			12			12			12	
Wtd Ab Crunch 3		15			15			20			20			25			25	
UPPER BODY STRETCHES																		
TUESDAY	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM
LADDER and HURDLES																		
Squat WU		10			10			8			8			6			6	
Squat 2		10			10			8			8			6			6	
Squat Jumps onto bench 1	bw	8			8			10			10			12			12	
Squat 3		10			10			8			8			6			6	
Squat Jumps onto bench 2	bw	8			8			10			10			12			12	
Squat 4																		
Single leg Calf Raise WU		10			10			8			8			6			6	
Single leg Calf Raise 2		10			10			8			8			6			6	
Single leg calf jumps 1	bw	8		bw	8		bw	10		bw	10		bw	12		bw	12	
Single leg calf jumps 2	bw	8		bw	8		bw	10		bw	10		bw	12		bw	12	
Single leg Calf Raise 3																		
Single leg ham curl WU		6			6			6			6			6			6	
Single leg ham curl 2		5			5			4			4			3			3	
Nordic Hamstring Stretch 1		12			12			16			16			20			20	
Nordic Hamstring Stretch 2		12			12			16			16			20			20	
Single leg ham curl 3																		
TURN OVER																		

NAME:

TUESDAY ctd	**WEEK 1**			**WEEK 2**			**WEEK 3**			**WEEK 4**			**WEEK 5**			**WEEK 6**		
	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM
Power Clean WU		6			6			4			4			6			6	
Power Clean 2		6			6			4			4			6			6	
Step-up Jumps 1	5	8		5	8		6	10		6	10		5	12		5	12	
Step-up Jumps 2	5	8		5	8		6	10		6	10		5	12		5	12	
Power Clean 3																		
Star Lunge 1		5			5			4			4			3			3	
Star Hops 1		6			6			8			8			10			10	
Star Hops 2		6			6			8			8			10			10	
Star Lunge 2		5			5			4			4			3			3	
1. Leg Lifts +		15			15			15			15			15			15	
1. Twisting Crunches		15	60		15	55		15	50		15	45		15	40		15	35
2. Leg Lifts +		15			15			15			15			15			15	
2. Twisting Crunches		15	60		15	55		15	50		15	45		15	40		15	35
3. Leg Lifts +		15			15			15			15			15			15	
3. Twisting Crunches		15			15			15			15			15			15	
LOWER BODY STRETCHES																		
WATER FOOTY SCORE:																		
FRIDAY	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM
WHOLE BODY CIRCUIT																		
Cable High Knee WU		12			12			12			10			10			10	
Cable High Knee 2		12			12			12			10			10			10	
High Knee MB throw 1		8			8			10			10			12			12	
High Knee MB throw 2		8			8			10			10			12			12	
Cable High Knee 3																		
Power Clean WU		6			6			8			8			6			6	
Power Clean 2		6			6			8			8			6			6	
Bag Lift 1		8			8			10			10			12			12	
Bag Lift 2		8			8			10			10			12			12	
Power Clean 3																		
Bench Press WU		12			12			12			10			10			10	
Bench Press 2		12			12			12			10			10			10	
Spring Bag Throws 1		8			8			10			10			12			12	
Spring Bag Throws 2		8			8			10			10			12			12	
Bench Press 3																		
Push Press WU		12			12			12			10			10			10	
Push Press 2		12			12			12			10			10			10	
Bag Throws 1	40	8		40	8		40	10		50	10		50	12		50	12	
Bag Throws 2	40	8		40	8		40	10		50	10		50	12		50	12	
Push Press 3																		
Underhand chin-ups 1																		
Underhand chin-ups 2																		
Reverse rope push-ups 1	bw	6		bw	6		10	6		10	6		15	6		15	6	
Reverse rope push-ups 2	bw	6		bw	6		10	6		10	6		15	6		15	6	
Underhand chin-ups 3																		
3*500m ROWING TIMES																		

Perform EACH GROUP OF EXERCISES in a 10 MINUTE BLOCK. TRY to stick to 2 MINUTE INTERVALS, however, if you are running out of time reduce the rest interval between the dynamic exercises, which are the 3rd and 4th set of each group. If you stick to this time limit each session including the warm-up and cool down will be finished in under 1 hour.

EXTRAS	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM	WT	RP	TM
5 MINUTE CYCLE																		
Lying Leg Lifts 1		15			15			20			20			25			25	
Lying Leg Lifts 2		15			15			20			20			25			25	
DB oblique raise 1		8			8			10			10			12			12	
DB oblique raise 2		8			8			10			10			12			12	
Lying Leg Lifts 3		15			15			20			20			25			25	
Triceps Pushdown WU		6			6			6			6			6			6	
Triceps Pushdown 2																		
Med Ball Pushdown throw 1	5	8		5	8		5	10		5	10		5	12		5	12	
Med Ball Pushdown throw 2	5	8		5	8		5	10		5	10		5	12		5	12	
Triceps Pushdown 3																		
Leg Press WU		6			6			6			6			6			6	
Leg Press 2																		
Single leg squat Jumps 1		8			8			10			10			12			12	
Single leg squat Jumps 2		8			8			10			10			12			12	
Leg Press 3																		
Biceps Curl WU		6			6			6			6			6			6	
Biceps Curl 2																		
Med Ball Juggle 1	5	8		5	8		5	10		5	10		5	12		5	12	
Med Ball Juggle 2	5	8		5	8		5	10		5	10		5	12		5	12	
Biceps Curl 3																		
Swiss Ball Twists WU		15			15			20			20			25			25	
Swiss Ball Twists 2		15			15			20			20			25			25	
Standing med ball passes 1	5	6		5	6		5	8		5	8		5	10		5	10	
Standing med ball passes 2	5	6		5	6		5	8		5	8		5	10		5	10	
Swiss Ball Twists 3		15			15			20			20			25			25	
SWIM	Laps =		10	Laps =		12	Laps =		14	Laps =		16	Laps =		18	Laps =		20

All exercises performed every 2 minutes
Try to do at least the same no. of reps during the third set of an exercise as you did during the 2nd set
Only record complete reps without assistance, if your spotter helps you don't count that rep
QUALITY IS ESSENTIAL! Don't perform reps with bad form, if your back bends when it shouldn't: STOP
If swimming at beach DO SOME INTENSE SWIMMING, not just paddling around

Figure D.2. The training program during the first pre-season microcycle.
The first column shows the day and exercises performed. These exercises are performed in vertical order, starting from the first exercise under the heading for the day. The subjects were required to fill in the weight lifted (WT), number of repetitions performed (RP) and the time at which each set was finished (TM) during the training session. If the RP is specified on the training program, this means that the subject was required to use a weight that would be appropriate for performing that number of repetitions. Where RP is blank, the subjects were required to perform as many repetitions as possible. Where TM is specified, this is the rest interval between this set and the next one.

NAME:

TUESDAY	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Warm-up: Ladder																		
Squat WU +		8			10			12			12			10			8	
Stiff leg deadlift WU		8			10			12			12			10			8	
Squat 1 +		8			10			12			12			10			8	
Stiff leg deadlift 1		8			10			12			12			10			8	
Squat 2 +			8			10			12			12			10			8
Stiff leg deadlift 2			8			10			12			12			10			8
Leg Press WU +		8			10			12			12			10			8	
Hamstring Curls WU		8			10			12			12			10			8	
Leg Press 1 +		8			10			12			12			10			8	
Hamstring Curls 1		8			10			12			12			10			8	
Leg Press 2 +			8			10			12			12			10			8
Hamstring Curls 2			8			10			12			12			10			8
Calf Raises 1 +		8			10			12			12			10			8	
Pulley Groin 1		8			10			12			12			10			8	
Calf Raises 2 +		8			10			12			12			10			8	
Pulley Groin 2		8			10			12			12			10			8	
Calf Raises 3 +			8			10			12			12			10			8
Pulley Groin 3			8			10			12			12			10			8
Ab Crunch 1 +																		
Roman Chair Leg Lifts 1																		
Ab Crunch 2 +																		
Roman Chair Leg Lifts 2																		

FITNESS - UPSTAIRS

FRIDAY	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Warm-up: Ladder																		
Power Clean WU +		4			5			6			6			5			4	
Bench Side Hop WU		6			6			6			6			6			6	
Power Clean 1 +		4			5			6			6			5			4	
Bench Side Hop 1		6			6			6			6			6			6	
Power Clean 2 +			4			5			6			6			5			4
Bench Side Hop 2			6			6			6			6			6			6
Reverse Hack Squat WU		8			10			12			12			10			8	
Reverse Hack Squat 1		8			10			12			12			10			8	
Reverse Hack Squat 2		8			10			12			12			10			8	
Nordic Hamstring WU		8			10			12			12			10			8	
Nordic Hamstring 1		8			10			12			12			10			8	
Nordic Hamstring 2		8			10			12			12			10			8	
Bench Press WU +		8			10			12			12			10			8	
DB Fly WU		8			10			12			12			10			8	
Bench Press 1 +		8			10			12			12			10			8	
DB Fly 1		8			10			12			12			10			8	
Bench Press 2 +		8			10			12			12			10			8	
DB Fly 2		8			10			12			12			10			8	
Bench Press 3 +			8			10			12			12			10			8
DB Fly 3			8			10			12			12			10			8
Push-up Jumps 1 +		8			10			12			12			10			8	
Rope Pull-ups 1		8			10			12			12			10			8	
Push-up Jumps 2 +			8			10			12			12			10			8
Rope Pull-ups 2			8			10			12			12			10			8

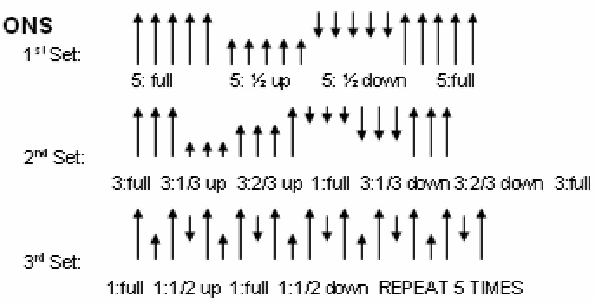
STRETCH - HAMSTRINGS, QUADS, GROIN

MONDAY	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Warm-up: 3x6 Bag throws																		
DB Bench WU +		8			10			12			12			10			8	
T-bar Row WU		8			10			12			12			10			8	
DB Bench 1 +		8			10			12			12			10			8	
T-bar Row 1		8			10			12			12			10			8	
DB Bench 2 +		8			10			12			12			10			8	
T-bar Row 2		8			10			12			12			10			8	
DB Bench 3 +			8			10			12			12			10			8
T-bar Row 3			8			10			12			12			10			8
Rack Clean WU +		8			10			12			12			10			8	
Underhand Chin-up WU		8			10			12			12			10			8	
Rack Clean 1 +		8			10			12			12			10			8	
Underhand Chin-up 1		8			10			12			12			10			8	
Rack Clean 2 +			8			10			12			12			10			8
Underhand Chin-up 2			-			-			-			-			-			-
Incline DB Bench 1 +		8			10			12			12			10			8	
Triceps Pushdown 1		8			10			12			12			10			8	
Incline DB Bench 2 +			8			10			12			12			10			8
Triceps Pushdown 2			8			10			12			12			10			8
Leg Lift Throws 1 +																		
Back Extensions 1																		
Leg Lift Throws 2 +																		
Back Extensions 2																		
Leg Lift Throws 3 +			-			-			-			-			-			-
Back Extensions 3			-			-			-			-			-			-
Forearm Bridge L +		8			10			12			14			16			18	
Forearm Bridge R		8			10			12			14			16			18	
Forearm Bridge L +		8			10			12			14			16			18	
Forearm Bridge R		8			10			12			14			16			18	

Figure D.3. The training program during the second pre-season microcycle.
This program follows a similar structure to the program provided in Figure D2. However, the time when each set is finished (TM) has been replaced with the repetition goal (GL). For the set with a number prescribed as the GL, the subjects performed as many repetitions as possible with a load that the investigator prescribed as a load that the individual subject should have been able to lift for the GL number of repetitions.

MONDAY	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
UPPER																		
Bench Press WU		10			10			10			12			12			12	
Bench Press 1		10			10			10			12			12			12	
Bench Press 2		10			10			10			12			12			12	
Bench Press 3		10			10			10			12			12			12	
Bench Press 4			10			10			10			12			12			12
Seated Row WU		10			10			10			12			12			12	
Seated Row 1		10			10			10			12			12			12	
Seated Row 2		10			10			10			12			12			12	
Seated Row 3		10			10			10			12			12			12	
Seated Row 4			10			10			10			12			12			12
DB Fly 1		10			10			10			12			12			12	
DB Fly 2		10			10			10			12			12			12	
Cable one arm pushdown 1		10			10			10			12			12			12	
Cable one arm pushdown 2		10			10			10			12			12			12	
DB Fly 3			10			10			10			12			12			12
LOWER																		
Squat		TIME	60		TIME	55		TIME	50		TIME	45		TIME	40		TIME	35
Hamstring Curl			60			55			50			45			40			35
Calf Raises			60			55			50			45			40			35

REPETITIONS



CORE	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Pelvis Lift 1		15			15			20			20			30			30	
Pelvis Lift 2		15			15			20			20			30			30	
Superman 1		15			15			20			20			30			30	
Superman 2		15			15			20			20			30			30	
Pelvis Lift 3		15			15			20			20			30			30	

For each of the lower body exercises you do ALL 3 sets. This means you do 9 LOWER BODY SETS!

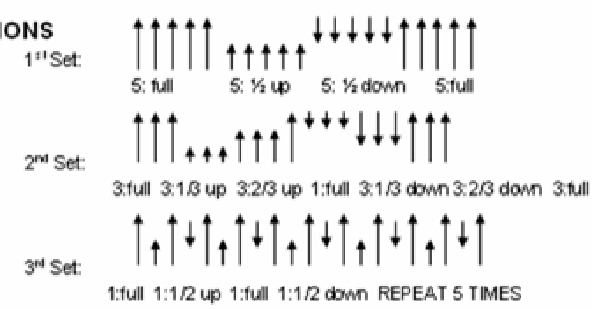
WEDNESDAY	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Bench Press WU		8			6			4			4			6			8	
Bench Press 1		8			6			4			4			6			8	
Bench Press 2		8			6			4			4			6			8	
Bench Press 3		8			6			4			4			6			8	
Bench Press 4			8			6			4			4			6			8
T-bar Row WU		8			6			4			4			6			8	
T-bar Row 1		8			6			4			4			6			8	
DB Pec Fly 1		8			6			4			4			6			8	
DB Pec Fly 2		8			6			4			4			6			8	
T-bar Row 2			8			6			4			4			6			8
Wide Grip Chins 1																		
Bag Lifts 1		8			8			10			10			12			12	
Jump Onto Bench 1		8			8			10			10			12			12	
Wide Grip Chins 2																		
Bag Lifts 2		8			8			10			10			12			12	
Jump Onto Bench 2		8			8			10			10			12			12	
Power Clean WU		8			8			8			8			8			8	
Power Clean 1		8			10			12			12			10			8	
Front Hack Squat 1		8			8			10			10			12			12	
Front Hack Squat 2		8			8			10			10			12			12	
Power Clean 2		8			10			12			12			10			8	
Standing Sit-ups 1		20			25			30			35			40			45	
Standing Sit-ups 2		20			25			30			35			40			45	
Forearm Bridge 1		10			12			14			16			18			20	
Forearm Bridge 2		10			12			14			16			18			20	
Standing Sit-ups 3		20			25			30			35			40			45	

Figure D.4. Control, full ROM subjects training program during the third pre-season microcycle.

This program follows a similar structure to the program provided in Figure D3. However, only two days of resistance training per week were performed. In addition, a matrix training scheme was integrated into the lower limb training program, with sets of matrix training performed for squat, hamstring curls and calf raises. This was included to increase lower body muscular endurance, however it would have had only a minimal influence on the results of this study.

MONDAY - LIGHT	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
UPPER																		
Bench Press WU		10			10			10			12			12			12	
Bench Press *FULL*		10			10			10			12			12			12	
Bench Press *3/4*		10			10			10			12			12			12	
Bench Press *HALF*		10			10			10			12			12			12	
Bench Press *1/4*		10			10			10			12			12			12	
Bench Press *FULL*			10			10			10			12			12			12
Seated Row WU		10			10			10			12			12			12	
Seated Row 1		10			10			10			12			12			12	
Seated Row 2		10			10			10			12			12			12	
Seated Row 3		10			10			10			12			12			12	
Seated Row 4			10			10			10			12			12			12
DB Fly 1		10			10			10			12			12			12	
DB Fly 2		10			10			10			12			12			12	
Cable one arm pushdown 1		10			10			10			12			12			12	
Cable one arm pushdown 2		10			10			10			12			12			12	
DB Fly 3			10			10			10			12			12			12
LOWER																		
Squat		TIME	60		TIME	55		TIME	50		TIME	45		TIME	40		TIME	35
Hamstring Curl		TIME	60		TIME	55		TIME	50		TIME	45		TIME	40		TIME	35
Calf Raises		TIME	60		TIME	55		TIME	50		TIME	45		TIME	40		TIME	35

REPETITIONS



CORE	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Pelvis Lift 1		15			15			20			20			30			30	
Pelvis Lift 2		15			15			20			20			30			30	
Superman 1		15			15			20			20			30			30	
Superman 2		15			15			20			20			30			30	
Pelvis Lift 3		15			15			20			20			30			30	

For each of the lower body exercises you do ALL 3 sets. This means you do 9 LOWER BODY SETS!

WED - HEAVY	WEEK 1			WEEK 2			WEEK 3			WEEK 4			WEEK 5			WEEK 6		
	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL	WT	RP	GL
Bench Press WU		8			6			4			4			6			8	
Bench Press *FULL*		8			6			4			4			6			8	
Bench Press *1/4*		8			6			4			4			6			8	
Bench Press *HALF*		8			6			4			4			6			8	
Bench Press *3/4*																		
Bench Press *FULL*			8			6			4			4			6			8
T-bar Row WU		8			6			4			4			6			8	
T-bar Row 1		8			6			4			4			6			8	
DB Pec Fly 1		8			6			4			4			6			8	
DB Pec Fly 2		8			6			4			4			6			8	
T-bar Row 2			8			6			4			4			6			8
Wide Grip Chins 1																		
Bag Lifts 1		8			8			10			10			12			12	
Jump Onto Bench 1		8			8			10			10			12			12	
Wide Grip Chins 2																		
Bag Lifts 2		8			8			10			10			12			12	
Jump Onto Bench 2		8			8			10			10			12			12	
Power Clean WU		8			6			4			4			6			8	
Power Clean 1		8			6			4			4			6			8	
Front Hack Squat 1		8			6			4			4			6			8	
Front Hack Squat 2		8			6			4			4			6			8	
Front Hack Squat 3			8			6			4			4			6			8
Power Clean 2			8			6			4			4			6			8
Standing Sit-ups 1		20			25			30			35			40			45	
Standing Sit-ups 2		20			25			30			35			40			45	
Forearm Bridge 1		10			12			14			16			18			20	
Forearm Bridge 2		10			12			14			16			18			20	
Standing Sit-ups 3		20			25			30			35			40			45	

Figure D.5. Experimental, variable ROM subjects training program during the third pre-season microcycle.

This program is identical to the control program, provided in Figure D4, with the exception of the bench press exercise. For this exercise the subjects were required to perform a combination of limited and full ROM sets.

Appendix E

ETHICAL APPROVAL AND INFORMED CONSENT

MEMORANDUM
From the Office of Research

Central Queensland
UNIVERSITY

Secretary, Human Research Ethics Committee
Ph: 07 4923 2603
Fax: 07 4923 2600
Email: ethics@cqu.edu.au

08 November 2005

Mr Ross Clark
Faculty of Arts, Health and Science
Building 6, Central Queensland University
Rockhampton QLD 4702

Dear Mr Clark,

HUMAN RESEARCH ETHICS COMMITTEE
ETHICAL APPROVAL
PROJECT: H05/09-105, *THE EFFECTS OF VARIABLE RANGE OF MOTION RESISTANCE TRAINING ON PERFORMANCE, MUSCLE FUNCTION AND ARCHITECTURAL PROPERTIES.*

The Human Research Ethics Committee is an approved institutional ethics committee constituted in accord with guidelines formulated by the National Health and Medical Research Council (NHMRC) and governed by policies and procedures consistent with principles as contained in publications such as the joint Australian Vice-Chancellors' Committee and NHMRC *Statement and Guidelines on Research Practice.*

On 01 November 2005 the Human Research Ethics Committee of Central Queensland University acknowledged your compliance to the conditions placed on your ethics approval for the research project, *The Effects of Variable range of Motion Resistance Training on Performance, Muscle Function and Architectural Properties.*

The period of ethics approval is 07 November 2005 to 28 February 2006. The approval number is H05/09-105, please quote this number in all dealings with the Committee.

The standard conditions of approval for this research project are that:

(a) you conduct the research project strictly in accordance with the proposal submitted and granted ethics approval, including any amendments required to be made to the proposal by the Human Research Ethics Committee;

(b) you report immediately anything which may warrant review of ethics approval of the project, including:
  (i) serious or unexpected adverse effects on participants;
  (ii) proposed changes in the protocol;
  (iii) unforeseen events that might affect continued ethical acceptability of the project;

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(A written report detailing the adverse occurrence or unforeseen event must be submitted to the Committee Chair within one working day after the event.)

(c) you provide the Human Research Ethics Committee with a written "Annual Report" by no later than 28 February each calendar year and "Final Report" by no later than one (1) month after the approval expiry date;

(A copy of the reporting pro formas may be obtained from the Human Research Ethics Committee Secretary, Nicole Turner please contact at the telephone or email given on the first page.)

(d) if the research project is discontinued, you advise the Committee in writing within five (5) working days of the discontinuation;

(e) you make submission to the Human Research Ethics Committee for approval of any proposed variations or modifications to the approved project before making any such changes;

(f) you comply with each and all of the above conditions of approval and any additional conditions or any modification of conditions which may be made subsequently by the Human Research Ethics Committee;

(g) you advise the Human Research Ethics Committee (email: ethics@cqu.edu.au) immediately if any complaints are made, or expressions of concern are raised, in relation to the project.

Please note that failure to comply with the conditions of approval and the *National Statement on Ethical Conduct in Research Involving Humans* may result in withdrawal of approval for the project.

You are required to advise the Secretary in writing within five (5) working days if this project does not proceed for any reason. In the event that you require an extension of ethics approval for this project, please make written application in advance of the end-date of this approval. The research cannot continue beyond the end date of approval unless the Committee has granted an extension of ethics approval. Extensions of approval cannot be granted retrospectively. Should you need an extension but not apply for this before the end-date of the approval then a full new application for approval must be submitted to the Secretary for the Committee to consider.

If you have any queries in relation to this approval or if you need any further information please contact the Secretary, Nicole Turner or myself.

Yours sincerely,

Dr Graham Davidson
Acting Chair, Human Research Ethics Committee

Cc: Project File
Dr Brendan Humphries (Other Investigator and Supervisor)

Application Category: A

School of Health & Human Performance
CQU

INFORMATION SHEET

THE EFFECTS OF VARIABLE RANGE OF MOTION RESISTANCE TRAINING ON PERFORMANCE, MUSCLE FUNCTION AND ARCHITECTURAL PROPERTIES

Investigator:

Mr Ross Clark
School of Health & Human Performance
Central Queensland University.
North Rockhampton, Qld. 4701
(07) 4930 9704
Email: r.clark@cqu.edu.au

Dr. Erik Hohmann

Dr. Brendan Humphries
School of Health & Human Performance
Central Queensland University.
North Rockhampton, Qld. 4701
Email: b.1.humphries@cqu.edu.au

Adam Bryant
Centre for Health, Exercise and Sports Medicine
School of Physiotherapy
Faculty of Medicine, Dentistry and Health Sciences
University of Melbourne
Email: albryant@unimelb.edu.au

OVERVIEW

The purpose of this study is to assess the effect of variable range of motion (VROM) training on performance and shape of the muscles. The following pages will provide you with information outlining the background of the study, the procedures that we will adopt and any possible risks or side effects associated with the study.

INTRODUCTION

Sports that involve contact and collisions, for example rugby league, require high levels of strength to be exhibited by the athlete. Training for these sports, especially at the elite level, requires an increase in force output by the athlete to improve their performance. VROM training may enhance the sport specific nature of resistance training by utilising loads and movements that more accurately resemble the nature of the sport than traditional full range of motion training.

VROM training consists of performing each set of an exercise throughout a different range of motion. For example, the athlete might perform 4 sets of bench press. During traditional training they would perform 4 sets of the exercise throughout the entire range of the movement with a similar load eg 100kg. In contrast, during variable range of motion training they would perform 1 set throughout the whole range of movement, 1 set through ¾ of the range of movement (from 15cm off the chest to full elbow extension), 1 set of ½ range of movement (from 30cm off the chest to full elbow extension) and 1 set of ¼ range of movement (from 45cm off the chest to full elbow extension). The same athlete may lift 100kg, 110kg, 125kg and 140kg for the full, ¾, ½ and ¼ range of movement sets respectively.

This study will examine various performance and muscle architectural features before and after you perform this method of training.

PURPOSE OF THE STUDY

The purpose of this study is to examine the effect of VROM training on performance and muscle shape and function.

SIGNIFICANCE OF THE STUDY

The results of this study will determine whether VROM training results in different muscular adaptations than traditional full range of motion training.

METHODS

This study will involve you participating in a 5 week whole body strength training program. This program will consist of 2 days per week of resistance training. These sessions will take place at the gym. All participants will perform an identical upper body training program except for the bench press. During this exercise you will either perform

VROM training or traditional full range of motion training, dependent on which group you are assigned to. Both methods have their potential benefits and drawbacks, and it is this studies aim to determine if there is a difference in performance measures between the 2 types of training protocols.

In this study you will also be required to attend 4 separate testing sessions, 2 performed before starting and 2 after finishing the training program. These sessions involve.

Sessions 1 and 3 (approximately 10 minutes per session):
For this session you will be required to go to Central Queensland Medical Imaging for ultrasound scans of your upper arm. The researcher will provide details on how to get there and what times it is necessary for you to attend.

<u>Ultrasound of the triceps</u>
These scans allow the researchers to determine the size and density of the muscles of your upper arm. The images taken will be shown to you after completion of the testing protocol, and will allow you to see what your arm actually looks like underneath the skin.

Sessions 2 and 4 (approximately 1 hr per session):
For this session you will be required to attend the Health and Human Performance Laboratory at Central Queensland University. The researcher will provide details on how to get there and what times it is necessary for you to attend.

<u>Warm-up</u>
The warm-up will consist of rowing at a steady pace for 5 minutes.

<u>Isokinetic bench press strength</u>
This test is a novel way of both testing and training the muscles involved in the bench press. The isokinetic bench press test requires the same movement as performed during a normal bench press. However, the movement is mechanically controlled so that no matter how hard you try and lift the bar it will always move at the same speed. This test will consist of 2 sets of 5 repetitions of full range of motion isokinetic bench press and 2 sets of 5 repetitions of half range of motion isokinetic bench press. Electromyography (EMG) will be performed during this test. This allows the researchers to see how much electrical activation is occurring in your muscles while you are lifting. This is done by placing electrodes on you chest and triceps. EMG is non-invasive and doesn't hurt at all.

<u>Isometric bench press strength</u>
This test shows us the maximum amount of force you can produce against an immoveable object. In this test you have to perform the bench press lift with a bar that is attached to a load cell. This load cell gives the researchers a measure of how much force you are producing. EMG will also be assessed during this test.

<u>Musculotendinous stiffness</u>

Musculotendinous stiffness is a measure of the elasticity of your muscles. The more elastic you are the more explosive your muscles are, however if you are stiffer you may have a greater potential for maximum strength. This test is very simple, requiring you to lay on a bench in the bench press position, holding a loaded bar. This bar is then tapped by the researcher and the yo-yo effect of your muscles is measured.

Bench throw tests

These tests are performed on the Plyopower. You will be required to perform 8 sets of 3 repetitions of bench throws with a 60kg load. Four sets will be performed throughout the full range of motion and 4 throughout only ½ the range of motion. Of the 4 sets in each range of motion, two will be performed with the bar starting on the chest and the other 2 will be performed with lowering and then throwing of the bar. These tests allow the researchers to test your potential to produce power.

Eccentric strength tests

Eccentric strength is an important factor in the prevention of injury. This test involves 2 sets of lowering a barbell in the bench press position from ¾ to ¼ of your bench press range of motion. The force you produce will be assessed to determine your ability to control external loading.

RISKS

You will be required to complete heavy load, maximal intensity training protocols during the period of this study. However, as you are accustomed to similar physical efforts during weight training the risks will be minimal. You will have been pre-screened to ensure that you do not have any existing medical conditions that may indicate that you should not undertake exercise. If any health risk factors are found that may affect your health or contra-indicate exercise participation, then you will be informed.

TEST	RISKS	EXPLANATION
Strength Testing	Fatigue, minor muscle damage	Testing will conducted in controlled conditions at the Health and Human Performance laboratory at Central Queensland University and conducted by qualified staff. The risk of injury and fatigue will be no greater than during a normal training session.
EMG	Minor discomfort	EMG requires the shaving and abrading of a small patch of skin on your chest and the back of you arm. This may cause a slight tingling sensation when the alcohol wipe is applied to clean the shaved section.

BENEFITS

If you choose to participate in this study, you will be performing testing sessions that double as cutting edge power training sessions.

The ultrasound scans being performed have a combined value of close to $1000 per person. These scans will allow you to see what the muscles of you upper arm actually look like.

You will also gain further understanding of what takes place at the university, especially in the Health and Human Performance Laboratory.

ABOUT MYSELF

I graduated with a Bachelor of Human Movement Science in 2002 and First Class Honours in Health and Human Performance in 2003. I have completed an internship at Acceleration Australia, Australia's first private performance enhancement centre. During this internship I was an assistant strength and conditioning coach for the Brisbane Bullets NBL team, AIC High School Rugby Union champions Ashgrove Marist College, and a number of elite athletes from a wide variety of sports. I have also completed work experience with the strength and conditioning coaches at the Richmond Tigers AFL club. In 2004 I was a strength and conditioning coach with the Queensland Reds Regional Development Squad. I am currently the strength and conditioning coach with your Central Queensland Comets rugby league team and the Queensland Academy of Sport. I am completing a Level 2 Australian Strength and Conditioning Association accreditation and have a strong interest in performance enhancement programs related to power sports.

Information About the Project

Before any testing is undertaken I will personally speak to each participant and ensure that they have an understanding of the protocols involved in the study. The two testing sessions will take place at CQU Rockhampton campus, in the Health and Human Performance Laboratory in Building 77.

Throughout the course of this study you are free to withdraw at any time for whatever reason without any penalty.

If at any stage during the testing or training you suffer from any negative effects (eg. injury) it is essential that you report this to one of the researchers. If necessary you will then be referred to the appropriate specialist.

The data and results of this study will be stored in a secure facility at Central Queensland University for 5 years. This data will be coded in a way that ensures your anonymity is maintained.

These results may be published in journals and presented at conferences and in interviews. However, at no stage will your individual results be revealed in a way that compromises your anonymity.

If you wish to receive a plain English copy of your results you can fill out the appropriate section on the consent form.

Enquiries:

Any enquiries or concerns about the proposed research can be directed to myself by ringing **(07) 4936-1174**, by e-mail at **r.clark@cqu.edu.au** or by writing to:

Ross Clark
c/o School of Health & Human Performance
Central Queensland University
North Rockhampton, QLD, 4702.

I will be pleased to answer any questions you have about my research project and your involvement.

Freedom to Withdraw

I have read the above information. The nature, the demands, risks and benefits of the project have been explained to me. I knowingly assume the risks involved, **and understand that I may withdraw my consent and discontinue participation at any time without penalty or loss of benefit to myself.** *In signing this consent form I am not waiving my legal claims, rights or remedies. A copy of the consent form will be given to me.*

Please contact Central Queensland University's Research Service Office (phone: 49232603) should there be any concerns about the nature and/or conduct of this research project.

Physical Activity Readiness Questionnaire

This form is a basic questionnaire designed to ensure that your participation in this program will be as safe as possible.

Name:____

Date of Birth:___/___/___

Are you presently suffering from any injuries that may limit your ability to participate in an exercise program? Yes / No (Please Circle One)
If yes list details of the injury:
____
____
____
____

Have you suffered any serious injuries such as broken bones, serious sprains or muscle, ligament or tendon damage in the past that may be aggravated by performing strenuous upper body exercise? Yes / No
If yes list details of injury:
____
____
____
____

Are you currently taking any prescribed medicines?
List details of medication:
____
____
____
____

Do you suffer from any medical conditions such as asthma, diabetes, allergies or epilepsy that could interfere with your ability to exercise? Yes / No
If yes list details of condition:
____
____
____
____

During the past twelve (12) months have you experienced:

- Faintness, lightheadedness or blackouts
- Unusual heartbeat
- Shortness or loss of breath when resting or doing light exercise (eg. walking)
- Pain or discomfort in your chest
- Asthma attacks

If yes to any of these, please list details:
____
____
____
____

Signature of Participant: ______________________________ Date: ___/___/___

Signature of Researcher: _______________________________ Date: ___/___/___

Signature of Witness: _______________________________ Date: ___/___/___

School of Health & Human Performance

CONSENT FORM

THE EFFECTS OF VARIABLE RANGE OF MOTION RESISTANCE TRAINING ON PERFORMANCE, MUSCLE FUNCTION AND ARCHITECTURAL PROPERTIES

CQUHREC Clearance No. H05/09-105

I consent to participating in this study and acknowledge that:

- I have been supplied with an Information Sheet discussing the purpose, aims, methodology and potential risks of the study, and that I have read and understood the contents of this form.
- Any queries I had concerning the Information Sheet or any aspects of the study have been answered to my satisfaction.
- I understand that my participation, non-participation or withdrawal from the study will have no effect on my academic standing or employment or quality of supervision I receive during training sessions.
- I understand that I may withdraw from the study at any stage without any negative consequences.
- I understand that my results will remain anonymous and confidential.
- The results of this study may be published or presented in any combination of a journal, thesis, oral presentation to the university, oral presentation to the public or presentation at a conference.
- I agree that I am providing my informed consent to participate in this research project.

Name (Family Name, Given Name(s)):____________________________________

Signature: ________________________ **Date:** _____________

Contact Number: _____________________________________

Please circle either YES or NO next to the statements below:

- I give permission for photographs or digital images of me to be used in the previously mentioned publications: YES NO

- I wish to receive a plain English statement of the results posted to me at the address listed below: YES NO

Address:____
____
____
____