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A comparative analysis of muscle activation profiles of elastic and weight resistance exercise.

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Abstract

The use of elastic materials is implemented as a resistance method for exercise in both rehabilitation and performance contexts. Despite the increasing popularity of this material, there is paucity of research on muscular responses that occur as a result of using it as a resistance method for exercise. The specific muscular activation patterns that occur throughout the range of motion (ROM) of an exercise can have a crucial impact on strength adaptations and their identification is imperative to the applicability of elastic training in different exercise settings. This project, therefore, aimed to provide an understanding of muscular responses elicited by elastic resistance during exercise.

The project consisted of five studies, of which four analytical and one intervention. The first study compared the patterns in muscular activation produced in response to exercising with elastic and weight resistance. Electromyographic responses of the agonist, antagonist and synergist muscles portrayed opposing muscular activation patterns with either method and higher activation of auxiliary muscles with elastic resistance. It was proposed that, due to the opposing activation patterns, the two methods may result in differing architectural adaptations of the skeletal muscles involved, indicating that they could be effectively used as complementary resistance methods. The higher engagement of auxiliary muscles further indicates that elastic resistance may be more effective at improving proprioception and joint stability than weight resistance.

The second study analysed the effect of movement velocity on muscular activation patterns with elastic and weight resistance. Peak muscular activation increased at higher velocities with both methods. However, the previously observed activation patterns (Study 1) became more pronounced at higher velocities, where peak activation occurred at earlier stages of movement with weight resistance, but remained at final stages of movement with elastic resistance. These results further indicate that architectural adaptations of the muscles involved may differ substantially with the long term implementation of either method, and that the combined use of elastic and weight resistance may prove beneficial in high speed resistance training in order to maximise muscle overload throughout the ROM.

The third study analysed the effects of combining half elastic and half weight resistance on muscular activation patterns. The combined condition portrayed a plateau in muscular activation for most of the concentric phase, as opposed to the peaks exhibited by the two methods on their own, and both the elastic and combined condition exhibited a greater engagement of secondary muscles than weight resistance, indicating that combining the two resistances does effectively maximise muscle overload throughout the concentric phase, offering the added benefit of engaging auxiliary muscles more than weight resistance alone.

The fourth study analysed the effect of multiple repetitions with either resistance method on electromyographic indicators of fatigue. Results indicated that elastic and weight resistances induce fatigue of the agonist muscle at similar rates, while synergist and antagonist muscles may fatigue at higher rates under elastic resistance.

The final study examined isokinetic and isometric strength adaptations at specific joint angles in response to eight weeks of bicep curl training with elastic resistance, weight resistance or a combination of the two. The opposing patterns in muscular activation elicited by the two methods, observed through the analytical studies, were reflected in angle-specific strength adaptations in the intervention study, where elastic training demonstrated a tendency to produce greater isometric strength gains at short muscle lengths, weight resistance tended to produce greater strength gains at stretched muscle lengths and the combination of the two resistances offered mixed responses. The findings indicate an effect of muscular activation pattern on angle specific strength adaptations, emphasizing the importance of understanding the specificity of muscular adaptations for the effective implementation of different resistance methods.

In conclusion, elastic and weight resistance produce opposing muscular activation patterns that are enhanced at high movement velocities and effectively complement each other when combined. The activation patterns were reflected in angle-specific strength adaptations through training, suggesting that they may produce different effects on changes in muscle architecture. Finally, auxiliary muscles were more active with elastic resistance, regardless of movement velocity or whether it was combined with weight resistance, indicating that the implementation of elastic resistance is more effective in improving proprioception and joint stability.

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Glossary of Terms and Abbreviations

The following abbreviations for terms and variables are used throughout this thesis:

Terminology:

Weight Resistance	Using free weights as a form of resistance for exercise
Elastic Resistance	Using elastic tubing as a form of resistance for exercise
Combined Resistance	Using both elastic tubes and weights in the same repetition
EMG	Electromyography
MVC	Maximal Voluntary Contraction
ROM	Range of Motion
1RM	1 Repetition Maximum

Variables:

SPV	Self-Paced Velocity
T0	Elastic tubes with no initial stretch
T10	Elastic tubes with a 10% reduction in initial length
T20	Elastic tubes with a 20% reduction in initial length
T60	Elastic condition where tube initial length is reduced by 10% and movement velocity is 60deg·s^{-1}
T120	Elastic condition where tube initial length is reduced by 10% and movement velocity is 120deg·s^{-1}
T180	Elastic condition where tube initial length is reduced by 10% and movement velocity is 180deg·s^{-1}
TW120	Combined condition where the load comprises of 50% weight and 50% elastic tension, the tube's initial length is reduced by 10%, and movement velocity is 120deg·s^{-1}
W60	Free weights, movement velocity is 60deg·s^{-1}
W120	Free weights, movement velocity is 120deg·s^{-1}
W180	Free weights, movement velocity is 180deg·s^{-1}

Introduction

1.1 Background

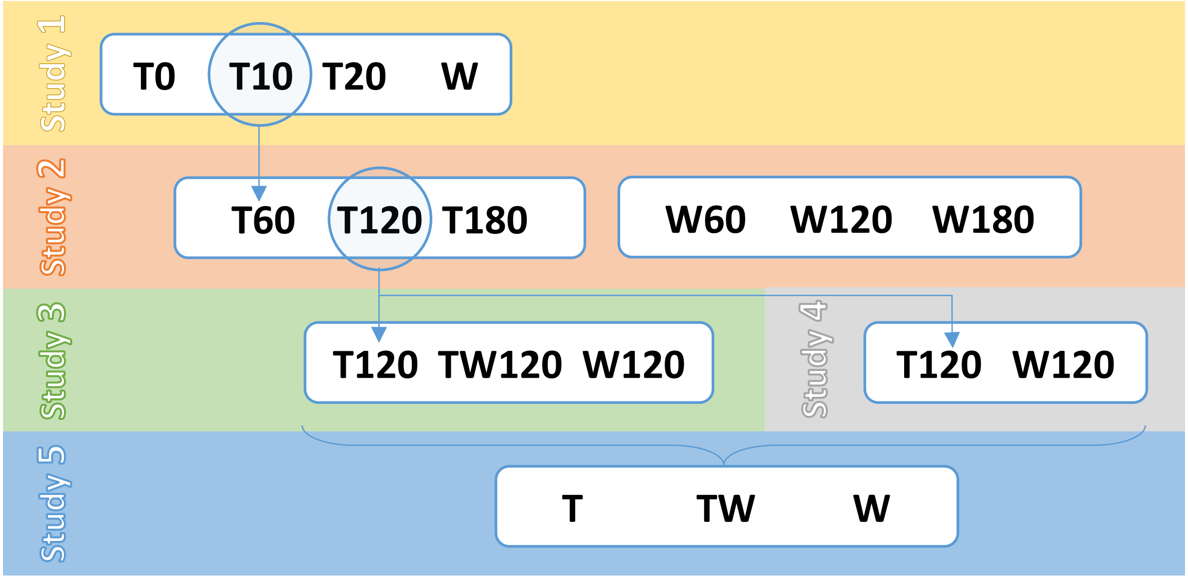
The advancement of technology during the industrial revolution brought about the extensive use of rubber and elastic materials, including their application as a method for resistance exercise in the early 1900s. Over a century later, elastic materials are now widely manufactured and advocated as a method of resistance for exercise, although there is a dearth of research on its efficacy, applicability and effects on muscular responses during exercise.

Elastic resistance training is considered an appropriate addition to weight resistance for both rehabilitation and performance contexts, although few investigations have tested the efficacy of elastic training against weight training through on either healthy or injured populations. The literature does present a wider selection of electromyographic studies on elastic resistance exercise, although the methods of data collection, the variability of the materials and the lack of standardisation between resistance methods have produced conflicting findings among studies, rendering results ambiguous and hard to compare. Studies validating the efficacy of elastic training against weight training are still needed in order to establish their applicability in a range of training contexts, from muscular rehabilitation to strength and conditioning.

This project aimed to provide a detailed understanding of muscular responses elicited by elastic resistance by comparing muscle activation patterns to those elicited by free weight training. This was done through four analytical studies, which detailed the specificity of muscular activation patterns throughout the entire range of motion, and a final strength training intervention study which compared muscular adaptations following training with elastic, weight or combined resistances. The main findings of these studies were gathered in a final summary of recommendations for the effective implementation of elastic resistance in various stages of rehabilitation and strength training.

1.2 Project Structure

The project comprised a series of analytical studies, focused on the understanding of muscular activation responses during elastic resistance training, culminating into a final intervention study to validate the observations gathered. The following section briefly outlines the variables analysed in each study and their connection to the following chapter.



Study 1 (Chapter 4 – Muscular activation patterns with elastic and weight resistance)

- Muscular activation responses to training with three initial tube stretches (T0, T10, T20) were compared to the manufacturer's recommended comparative weight (W). Movement velocity was kept at 60deg·s^{-1} in order to minimise the impact of momentum on muscular responses.
- It was observed that T10 elicited the most similar muscular activation to W. A 10% initial tube stretch was therefore applied to the elastic condition in all subsequent studies. [T10 = T60]

Study 2 (Chapter 5 – The effect of velocity on muscular activation patterns)

- Muscular activation responses at three movement velocities (60deg·s^{-1}, 120deg·s^{-1}, 180deg·s^{-1}) were compared between elastic (T60, T120, T180) and weight resistance (W60, W120, W180).
- Training velocity 120deg·s^{-1} was found to be most similar to average self-paced velocities, 120deg·s^{-1} was therefore used in all subsequent studies.

Study 3 (Chapter 6 – Combining elastic and weight resistance)

- Elastic and weight resistance at 120deg·s^{-1} training were compared to a combined condition (TW120) using both resistances at the same time.
- The three conditions (T120, TW120, W120) were found to produce different muscular activation patterns, and were therefore all included in the intervention study (Study 5).

Study 4 (Chapter 7 – Rates of fatigue with elastic and weight resistance)

- The repetition effect was compared between elastic and resistance training at 120deg·s^{-1}.
- Tubes (T120) and weights (W120) were found to elicit similar rates of fatigue, these findings would be used to aid in the interpretation of the results in Study 5.

Study 5 (Chapter 8 – Eight-week intervention study)

- All three conditions (T, TW, W) were used in a home-based intervention study on bicep curls

Literature Review

This chapter presents a review of the literature pertinent to this thesis, underpinning the mechanisms of muscular responses and adaptations during strength training, with a particular focus on the effects of elastic resistance exercise. The following sections will first address the general aspects of resistance training, its influencing factors and effects on neural and muscular adaptations, followed by a review of the literature related to elastic resistance and its effects on muscular activation and adaptations.

2.1 Adaptations to resistance training

The most intuitive understanding of resistance training regards its task-specificity; where speed, load and duration of the exercise are expected to produce adaptations that are pertinent to the training modality being employed (De Lorme, 1945). Decades of research have supported this theory with empirical evidence, elucidating the mechanisms involved in producing such adaptations and giving better insight into their applicability (Ingebrigsten *et al.*, 2009; Thomas *et al.*, 2007; Campos *et al.*, 2002). Understanding these mechanisms enables researchers to predict how different training methods will affect performance, where the principle of specificity may not always be perfectly applicable and adaptations can be carried over to different contexts. Examples of this include the increase in cycling aerobic power or the enhancement of running economy following leg resistance training, despite a lack of increase in VO_{2max} (Campos *et al.*, 2002; Paavolainen *et al.*, 1999). Therefore, in anticipation of exploring the applicability of elastic resistance, this section will review general muscular adaptation mechanisms involved in resistance training.

2.1.1 Resistance training: what is it and what factors influence it?

Resistance exercise includes any form of movement performed with a load, which can be provided by a number of methods or materials and can be classified as isotonic or variable. Isotonic resistance methods involve the use of an unchanging load such as free weights or pulley machines, while variable resistances implement loads that change in dependence to movement velocity, direction of applied force and compression or stretch of the material; these methods may include the use of springs, hydraulic or pneumatic pressure and elastic materials (Frost *et al.*, 2010). While isotonic resistance methods have been widely investigated for over a century (Berryman and Park, 1992), variable resistance methods are not yet fully understood. The specificity of the latter, and the high number of variables that they present, render them less intuitive than weights in terms of muscular responses and adaptations and, consequently, rather difficult to standardise and compare with more common methods.

The discernment of how different loads influence muscle behaviour lays on the understanding of basic mechanisms of excitation and contraction of the neuromuscular system. Regardless of the type of load implemented, skeletal muscles respond to external force by contracting, a mechanism that involves the sliding of two contractile filaments (actin and myosin) to shorten (concentric) or lengthen (eccentric) the muscle. Concentric muscle actions involve a shortening of the muscle fibres due to the overlapping of the contractile filaments, effecting a change in joint angle. Eccentric actions consist in the active lengthening of the muscle and are normally involved in the deceleration of a movement, such as preventing a dumbbell from quickly extending the elbow, or shock absorption when landing from a jump. Thirdly, isometric muscle actions are regarded as an activation of the muscle fibres without a change in the length of the muscle. These contractions are more commonly involved in the stabilization of static joints.

While concentric actions are the most common form of contraction during exercise, it is widely accepted that eccentric training produces the greatest strength gains compared to concentric or isometric training (Crewther *et al.*, 2005). During the active lengthening of sarcomeres in an eccentric action, myosin heads remain attached until the excessive stretch forcibly detaches the cross bridges. These heads quickly reattach to the next actin binding site, making eccentric actions the most efficient form of contraction (Franchi *et al.*, 2017), characterised by a lower motor unit recruitment (Behm, 1995) and a lower metabolic cost with respect to concentric actions (Hoppeler *et al.*, 2016), providing the potential for greater force generation. The efficiency of eccentric actions enables supramaximal loads to be implemented, hence producing greater strength gains. However, eccentric actions alone do not appear to provide any added benefits compared with concentric actions given that, at equal loads, concentric-only and eccentric-only training result in equivalent strength gains (Roig *et al.*, 2008). This indicates that, during dynamic resistance training, the eccentric portion of movements contributes as much as the concentric portion to muscular adaptations. Therefore, identifying whether different resistance methods elicit differing magnitudes of eccentric or concentric activation may help predict outcomes in strength adaptations to each form of exercise. This requires an investigation of both neural and physiological responses involved during exercise and an understanding of the consequential adaptations that may occur.

2.1.2 Neural adaptations

It has been extensively demonstrated that increments in muscular strength are mediated by neural adaptations that are most often detected prior to hypertrophy (Knight and Kamen, 2001; van Cutsem *et al.*, 1998; Hakkinen and Komi, 1983). The signal for contraction begins in the central nervous system, upper motoneurons from the corticospinal tract then impinge on α-motoneurons in the spinal cord, which then deliver the signal to the muscle through excitation-contraction coupling in motor units. Neural adaptations can occur at any point along this circuit (Carroll *et al.*, 2006; Kordosi *et al.*, 2014; Kamen and Knight, 2004)).

There is some evidence of central neural adaptations and changes in cortical mapping occurring at initial stages of training. A meta-analysis by Carroll *et al.* (2006) reported that unilateral strength training produced an average increase in contralateral limb strength of 8% (half of the trained limb), suggesting that strength gains may be partially mediated by adaptive increases in central neural drive (Kordosi *et al.*, 2014; Carroll *et al.*, 2006). In addition, Pascual-Leone *et al.* (1994) observed progressive changes in cortical output maps during motor skill acquisition, suggesting that adaptive changes in central neural activity patterns may also play an important role in the development of muscular function.

More evident neural adaptations are however likely to occur in the peripheral nervous system, where increases in voluntary muscle activation have been observed in concomitance with increases in strength at early stages of strength training (Seynnes *et al.*, 2007; Kamen and Knight, 2004; Knight and Kamen, 2001) while hypertrophy is often only observed after the first 8 weeks of exercise (Knight and Kamen, 2001). Improvements in maximal strength and rate of force development have been associated with an observed increase in EMG amplitude and frequency following resistance training (Knight and Kamen, 2001; Cronin *et al.*, 2003). The neuromuscular processes that mediate these increases may involve an improvement in motor unit recruitment and synchronization, resulting in an increased number of active motor units at the onset of contraction (van Cutsem *et al.*, 1998), effecting the increase in amplitude and firing frequency observed in EMG readings (Aagard *et al.*, 2003; Cronin *et al.*, 2002; Patten *et al.*, 2001; Yao *et al.*, 2000; Van Cutsem *et al.*, 1998). Overall increases in motor unit activation, measured via the integration of the EMG signal, have also been observed following resistance training (Hakkinen *et al.*, 2003; Hakkinen *et al.*, 2001) and maximal EMG amplitude appears to increase following power training (Knight and Kamen, 2001). These observations clearly demonstrate that initial strength gains are mediated by an increased neural drive, where greater overall motor unit activation produces greater strength output (van Cutsem *et al.*, 1998), while motor unit discharge rate is more specifically associated with the muscle's rate of force development (Aagard *et al.*, 2003; Nelson, 1996).

These neuromuscular adaptations, though more prominent during early stages of training, continue at lower rates in trained individuals (Patten *et al.*, 2001) and may involve the downregulation of inhibitory pathways. It is suggested that neural inhibition at corticospinal level, mediated by Renshaw cells, limits the potentiation of maximal contractions in untrained individuals, particularly at low movement velocities, which may be reduced with resistance training (Aagaard *et al.*, 2003, 2000). Renshaw cells, a class of inhibitory neurons located in the spinal cord, impinge collaterally on α-motoneurons and are therefore stimulated when these activate. The Renshaw cell axon feeds back to the α-motoneuron soma applying an inhibitory signal, hence reducing the firing frequency of the post-synaptic neuron (Figure 2.1). The signal that passes from the upper motoneuron to the α-motoneuron is therefore reduced. Renshaw cell inhibition is proposed to protect muscles from excessively high frequencies, where inhibitory strength increases with multiple pulse stimulation of the upper motoneurons (Bhumbra *et al.*, 2014), and may play an important role in the reduction of motor unit signalling in untrained individuals. Although no evidence of Renshaw cell adaptation exists, their inhibitory role in muscle contraction suggests that the proposed changes in neural circuitry pathways may involve a reduction of Renshaw inhibitory signals (Moore *et al.*, 2015; Aagaard *et al.*, 2003).

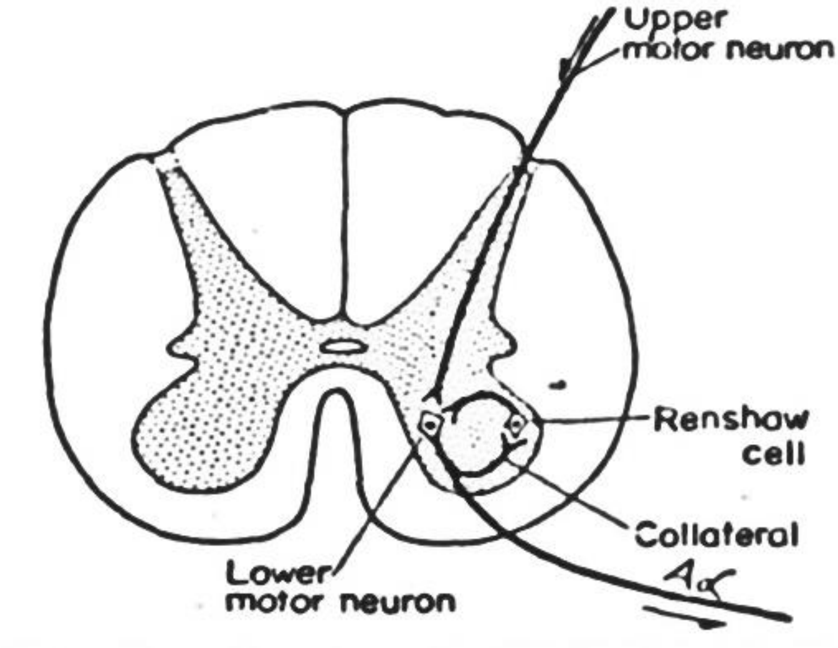


Figure 2.1 – Diagram of Renshaw cell circuitry in the spinal cord (Kudrin, 2010).

High intensity resistance training appears to be most effective in producing neural adaptations. Kamen and Knight (2004) found increases in motor unit firing frequency after 6 weeks of training with maximal contractions, but not with 50% or 10% of maximum, indicating that, while 6 weeks of high intensity training produce neural adaptations, this may not be sufficient time to overcome the inhibitory mechanisms at lower intensities. However, Fernandez Del Olmo *et al.* (2005) found evidence of sustained neural adaptations to resistance training, including an increased voluntary activation at low intensities in experienced resistance trainers (>2years), suggesting that neural adaptations occur at all training intensities, and continue to occur even as the training level progresses.

Factors that directly influence neuromuscular adaptations include time under tension, training load and movement velocity. Tran *et al.* (2006) reported that increasing time under tension increased neuromuscular fatigue, proposing that this would also result in greater strength gains. In support of this speculation, Burd *et al.* (2012) found that, in trials with matched work loads, greater time under tension significantly increased protein synthesis even at low intensity strength training (30% repetition maximum), demonstrating that time under tension induces both neural and physical adaptations that contribute to increments in strength. Thus, understanding whether different resistance methods produce differing load and activation patterns, and consequently different time under tension spans, can give better insight to their applicability.

In summary, neuromuscular adaptations occur from early stages of training, continue as exercise progresses and are directly proportional to the intensity of training. Therefore, the factors that influence these adaptations, such as time under tension, load and movement velocity, should be kept in consideration when devising exercise programmes. Equally as important is the understanding of how different methods of applying resistance affect activation patterns and how these may influence neuromuscular adaptations during training.

2.1.3 Physical adaptations

Muscle hypertrophy is the most common physical adaptation observed in concomitance with exercise; it is related to strength improvements and refers to the increase in muscle size due to an enlargement of the individual muscle fibres. Key to muscle hypertrophy is the growth and proliferation of myofibrils. A review of the current literature gives insight to the sequence of mechanisms that are suggested to effect an increase in fibre cross sectional area (Folland and Williams, 2007). Myofibrillar growth has been observed in response to resistance training, where newly formed contractile proteins fuse with existing sarcomeres, increasing their volume (Goldspink and Howells, 1974). Unbound fragments of contractile proteins are normally found in the periphery of myofibrils (Folland and Williams, 2007). Their synthesis is stimulated by physical activity and is regulated by the expression of multiple genes that determine the specific isoforms of actin and myosin phenotype expression, ultimately devising the contractile characteristics of the muscle fibre type (Wang *et al.*, 2005; Lin *et al.*, 2002). A discrepancy in Z-disk alignment due to the addition of peripheral filaments to existing sarcomeres is suggested to cause a longitudinal rupture of the myofibril, hence effecting proliferation (Folland and Williams, 2007). Within muscle fibres however, each myonucleus has a limited cytoplasmic volume capacity (higher in type II fibres than in type I), which limits their growth. An increased proliferation of satellite cells occurs during resistance training, where one daughter cell differentiates into a myonucleus and fuses with existing fibres, providing them with greater capacity for growth via an increased synthesis of contractile proteins, thus enabling hypertrophy to occur (Folland and Williams, 2007). In addition, muscle fibres appear to retain their added myonuclei even after atrophy, which may explain their ability to quickly regain strength during re-training (Bruusgaard *et al.*, 2010).

Morphological adaptations to resistance exercise include the longitudinal and cross sectional growth of muscle fibres, which implies the in-series and in-parallel proliferation of myofibrils. The cellular mechanisms responsible for producing these configurations are not yet fully understood, although the biomechanical factors that influence the plasticity of muscle architecture have been recently investigated, including the exertion of muscles along the force-length and the force-velocity relationship curves, as discussed in the following sections.

2.2 Force-velocity relationship during resistance training

The force-velocity relationship of muscle shortening is defined by the ability of skeletal muscles to move greater loads at lower velocities and lighter loads at greater velocities (Bigland and Lippold, 1954). While this conveys that fast contractions are only possible with relatively low resistances, a Position Stand by the ACSM (2002) identified two types of slow contractions: unintentional and intentional. Heavy loads are responsible for limiting movement velocity during unintentionally slow contractions and elicit high muscular activations, while intentionally slow movements portray lower force outputs and exhibit lower motor unit activity than fast movements. Consequently, at equal loads, high velocities (180-240deg·s^{-1}) induce the greatest strength adaptations due to an increased motor unit discharge during contraction (Munn *et al.*, 2005; Kanehisa and Miyashita 1983). Studies have also demonstrated a velocity-specific training effect where, although strength adaptations are somewhat transferrable between velocities (Behm, 1991; Kanehisa and Miyashita 1983) they are mostly retained at the velocity used during training (Ingebrigsten *et al.*, 2009; ACSM, 2002; Bell *et al.*, 1989).

Adaptations to high speed training include changes in fibre type, muscle hypertrophy, increase in fibre pennation angle and fascicle length (Blazevich and Sharp, 2005). Neural adaptations are especially enhanced at higher training velocities, where ballistic and high speed training increase maximal firing frequency of motor units and decrease time to peak activation, therefore mediating increases in rate of force development and speed of contraction following high speed training protocols (Knight & Kamen, 2001; Aagaard *et al.*, 2000; van Cutsem *et al.*, 1998).

While very low velocities have been found to produce significant strength adaptations and an increase in type I fibre area (but not type II) in untrained individuals (Schuenke *et al.*, 2012; Gillies *et al.*, 2006), the longer duration of a slow contraction requires a reduction in the load for highly trained individuals, thus limiting adaptations in maximal strength (Kanehisa and Miyashita, 1983). The ACSM Position Stand, therefore, recommends that low velocities be used for untrained individuals, increasing the training speed as the participant becomes more accustomed to resistance training (ACSM, 2002).

The ability of a muscle to generate force rapidly is therefore dependent on its ability to produce high muscle activations at the onset of contraction, which can be improved through training (Maffiuletti *et al.*, 2016). However, alongside the high initial EMG activations, high movement velocities exhibit a marked fall in EMG at final phases of movement (Sakamoto and Sinclair, 2012). Although the initial peak in activation is key to producing adaptations in high speed contractions, the contrasting decline in activation at the end of the movement can be seen as a limitation of non-ballistic training for power. The decline in activation is a consequence of both limb biomechanics and movement velocity. Due to their dependence on gravitational forces, many weight lifting exercises present a so called 'sticking point', where the exercising limb is at mechanical advantage against the weight due to a reduction of the moment arm to a minimum, requiring minimal contribution of the agonist muscle. Furthermore, the deceleration of the movement that the athlete performs in order to avoid projecting the weight during high speed training causes a lower activation, and force production, of the agonist muscle (Swinton et al., 2014). In order to retain muscular overload throughout the entirety of the range of motion, Behm (1988) suggested adding elastic bands as a form of resistance, expecting the muscles to retain their level of activation as the material stretched at final phases of movement. Although Behm's (1998) suggestion is highly plausible, and the addition of elastic resistance to free weights has also been suggested by other authors (Jakobsen *et al.*, 2013; Frost *et al*, 2010), the specific effects of elastic resistance on muscular activation patterns at high velocities have not yet been investigated, rendering it difficult to substantiate this proposal.

To date, there have been few publications on the effects of muscle action velocity during elastic training, where higher movement velocity has been found to elicit higher overall muscular activation than lower velocities under elastic resistance than it does for weight resistance (Jakobsen *et al.*, 2013; Matheson *et al.*, 2001). However, considering the variable resistance that elastic materials offer, there is a need to better understand the activation patterns that occur throughout the ROM during elastic resistance exercise at different velocities.

2.3 Length-tension relationship of skeletal muscles

The force-length relationship of muscles describes the capacity of skeletal muscles to generate a maximal amount of force at an optimal length. This relationship is dependent on the smaller contractile units called sarcomeres, which are in turn composed of two sliding filaments: actin and myosin (Figure 2.2) (Rassier *et al.*, 1999). Actin and myosin filaments overlap throughout the sarcomere and interact through cross-bridges: binding sites that enable the myosin to "crawl" towards the centre of the actin filament, causing the muscle to contract and shorten. An optimal filament overlap length exists where muscles are able to produce the greatest amount of force (Rassier *et al.*, 1999). When sarcomeres are stretched, or contracted, away from this optimal overlap, their force generating capacity decreases. This phenomenon is also called length-tension relationship and is an alterable characteristic of skeletal muscles (Brughelli *et al.*, 2010).

The muscle's capacity to generate force along the length-tension relationship curve is affected by the number of in line sarcomeres contained in the muscle fibres and is adaptable through strength training, where long term strength adaptations to exerting the muscle at long lengths have been found to increase the number of in-line sarcomeres per fibre, while exerting the muscle at shorter lengths has been found to decrease their number (Brughelli *et al.*, 2010; Rassier *et al.*, 1999). Consequently, training at long muscle lengths causes a shift in peak torque towards longer muscle lengths (Brockett *et al.*, 2001), and likewise for short muscle lengths (Rassier *et al.*, 1999). Alegre *et al.* (2014) found that training at a 90° knee angle caused a shift in peak torque towards longer muscle lengths of the knee extensors, while training with a more extended knee caused a shift towards shorter muscle lengths. This shift in the length-tension relationship curve can be attributed to a change in the muscle's architecture caused by the adaptability of sarcomere units. It has also been established that sarcomeres of a same fibre are not uniform in length, and that the number and length of sarcomeres can decrease or increase in adaptation to training and injury (Timmins *et al.*, 2016). Consequently, engaging in sports that exert the muscle at shorter lengths (i.e. cycling) have been found to cause a decrease in sarcomere number and resultant increase in sarcomere length, while exercising at long muscle lengths (i.e. running) produces an increase in sarcomere number and decrease in length (Brughelli *et al.*, 2010; Rassier *et al.*, 1999; Herzog *et al.*, 1991; Lynn and Morgan, 1994).

Most importantly, long sarcomeres not only have a reduced capacity for force generation when stretched, but are also weaker than short sarcomeres when exerted at stretched lengths (Rassier *et al.*, 1999). Muscles that have fewer in line sarcomeres are therefore weaker on the descending limb of the force-length relationship curve (Figure 2.2) and are more prone to muscle damage (Timminis *et al.*, 2016). In addition, Timmins *et al.* (2015) found that, after injury, the contractile portions of repaired muscle fibres become shorter, resulting in fewer, and longer, in-series sarcomeres and a consequent shift in peak force toward shorter muscle lengths making the muscle weaker and more prone to repeated injury (Brughelli *et al.*, 2010; Rassier *et al.*, 1999). Accordingly, after examining previously injured hamstrings in elite athletes, Brockett *et al.* (2004) and Proske *et al.* (2004) found that, despite retaining the same peak strength values, the injured leg generated peak force at significantly smaller knee angles than the uninjured leg, where hamstrings are more shortened. Consequently, muscles that generate peak force at shorter lengths have largely been associated with higher injury risk (Brughelli and Cronin, 2007).

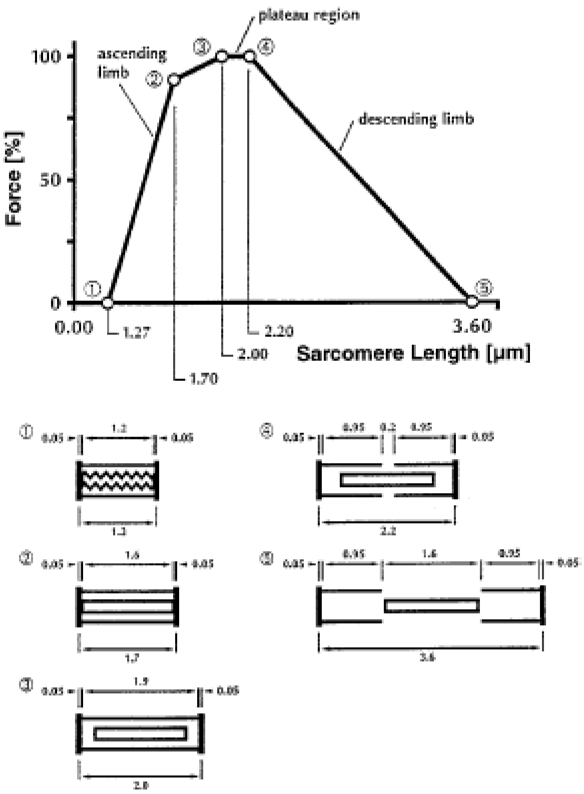


Fig. 2. Force-length relationship of frog skeletal muscle sarcomere, as derived first by Gordon et al. (28) (*top*), and schematic sarcomeres corresponding to crucial points (*1–5*) labeled on the force-length curve (*bottom*).

Figure 2.2 – Force-length relationship from Rassier et al. (1999)

Given that exercise at longer muscle lengths can stimulate an increase in sarcomeres per muscle fibre, producing shorter, stronger sarcomeres and therefore shifting peak force to greater lengths (Rassier *et al.*, 1999), it can be recommended that previously injured muscles should be trained at longer muscle lengths in order to prevent further injuries. This adaptability of muscle fibres stresses the importance of understanding muscular activation patterns during novel training methods in order to assess the implications of shifting peak activation to different muscle lengths for sport specific strength adaptations and injury risk.

2.3.1 Movement velocity and muscle architecture

Muscle shortening velocity is dependent on muscle fibre type composition, pennation angle and fibre length, where a higher composition of type II muscle fibres, a greater pennation angle and longer fibres are associated with faster contractions (Cormie *et al.*, 2011; Blazevich & Sharp, 2005; Wickiewicz *et al.*, 1984). Muscles with longer fibres, which presumably contain more (and shorter) in-series sarcomeres, display higher shortening velocities than shorter fibres at equal force outputs given that the shortening velocity of a fibre is a function of that of each contractile unit (Wickiewicz *et al.*, 1984). This characteristic has been associated with performance, where sprint runners portray longer fascicles than distance runners (Abe *et al.*, 2000) and fascicle length is further correlated with sprint performance among trained short distance runners (Kumagai *et al.*, 2000).

In another study on trained sprinters, Blazevich *et al.* (2003) observed that 5 weeks of high-speed jump/sprint training elicited an increase in fascicle length of the quadriceps muscles, which was not observed when adding resistance training to the routine. Intuitively, one could argue that the high-speed training group focused muscular exertion at longer muscle lengths, where both jumping and sprinting would be expected to produce higher muscular activations at initial phases of movement where the quadriceps are stretched, while weight resisted squats would arguably exert the muscle throughout a wider portion of the ROM, including shorter muscle lengths. Thus, it is plausible to suggest that the architectural changes observed by Blazevich *et al.* (2003) may have been caused by higher magnitudes of muscle activation at long muscle lengths which would have influenced the ratio of in-series sarcomeres per fibre (Brughelli *et al.*, 2010; Rassier *et al.*, 1999). In support of this assumption, Stasinaki *et al.* (2015) found that coupling strength and power exercises in the same session resulted in no improvements in power performance and a decrease in fibre length. Increases in muscle fibre length are therefore clearly associated with high velocity training programmes, although the mechanism responsible for the elongation of the fibres has still not been elucidated. By displaying the muscular activation patterns elicited by different movement velocities, this thesis aims to provide information that may shed light on the factors involved in architectural adaptations of the skeletal muscle at different training velocities.

2.4 Muscular fatigue and electromyography

Fatigue is generally described as the progressive decline of performance during sustained activity (Allen *et al.*, 2008) eventually reaching reversible momentary muscular failure (Enoka and Stuart, 1992). It is a broad and complex topic, pertinent to all training modalities from endurance to strength training, through different mechanisms. Fatigue can be caused by the impaired function of a number of systems, including the cardiorespiratory system, neural transmission from central to peripheral nervous systems, excitation-contraction coupling mechanisms or biochemical contraction mechanisms within the skeletal muscle itself (Davis *et al.*, 2000).

In a review on physiological models of fatigue, Noakes (2000) described the importance of central nervous system fatigue and a reduction in myofibril contractility during fatigue for inducing neural and biomechanical adaptations that mediate an increase in maximal force output and rate of force development. The former is caused by increases in brain serotonin concentrations as a result of prolonged exercise (>10 minutes), which mediates a reduction in the density of neural impulses that reach the muscle, hence affecting rate of fatigue (Davis *et al.*, 2000). Adaptive increases in central neural drive are therefore suggested to improve performance by increasing skeletal muscle recruitment (Noakes, 2000). Another model described by Noakes (2000) argues that biochemical alterations in the contraction process, including the disruption of Ca^{2+} delivery within muscle fibres, affect the contractility of the myofibrils, inducing local muscular fatigue. For the purpose of this project, this section will focus particularly on cellular mechanisms involved in the excitation-contraction coupling of muscles and its relevance in the detection of fatigue through electromyography.

Muscle contractions are initiated via neural excitation in the nervous system, where an action potential in the motoneuron is transmitted to the muscle via the release of acetylcholine. The transmission of the action potential across the neuromuscular junction and through the sarcolemma initiates an action potential in the T-tubules, causing the sarcoplasmic reticulum to release Ca^{2+} into the myoplasm. Within the sarcomeres, Ca^{2+} binds to troponin C causing a change in the conformation of tropomyosin, exposing the actin-myosin bindings sites and enabling the cycling of cross bridges, prompting muscle contraction. This sequence is illustrated in Figure 2.3, below.

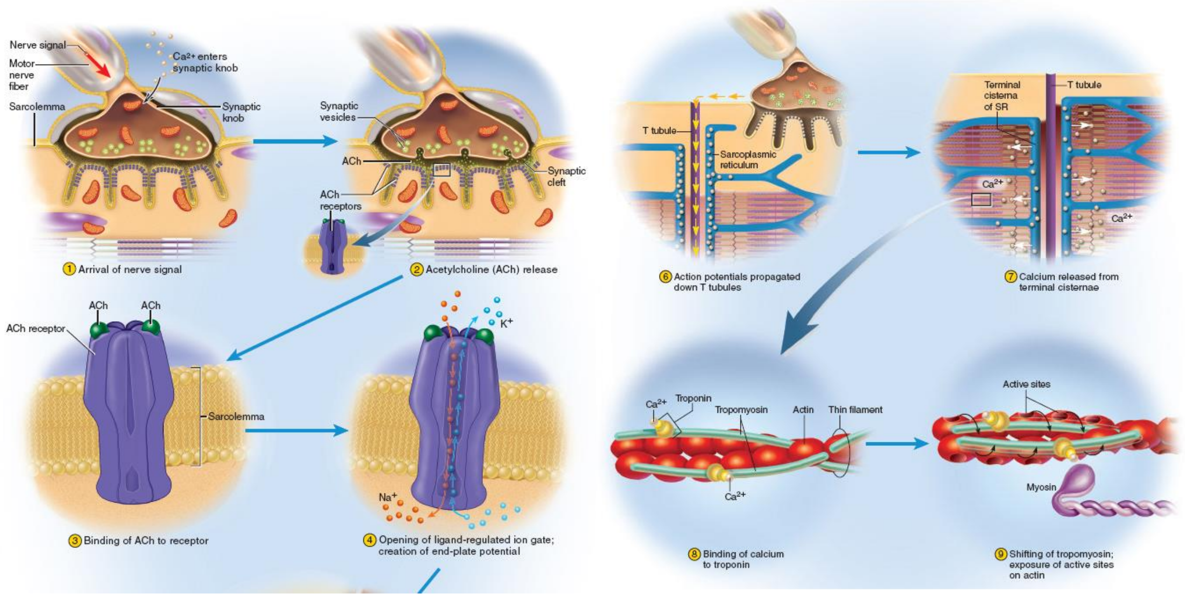


Figure 2.3 – Excitation-contraction coupling sequences (HHSC, 2017).

Such mechanisms are dependent on electrochemical gradients of components such as Na+ and K+ that regulate the propagation of the action potential across the sarcolemma. Normal physiological conditions involve a low K^+ - high Na^+ extracellular concentration and high K^+ - low Na^+ intracellular concentration. As the action potential propagates across the sarcolemma, voltage-dependant channels allow Na+ to enter the cell and K+ to exit the cell, while a Na^+-K^+ pump drives the ions back to their original sites to maintain the required electrochemical gradient. When muscles are contracted repeatedly, the efflux of K^+ through voltage-dependant channels, and an increased leakage of K^+

through ATP-sensitive channels, lead to an increase in extracellular K^+ which is not sufficiently compensated by the Na^+-K^+ pumps, causing membrane depolarization and reduced excitability (Allen *et al.*, 2008; Fortune and Lowery, 2007). Increased levels of interstitial K^+ have in fact been associated with a decrease in muscle fibre conduction velocity during electromyographic studies (van Dieen *et al.*, 2009; Juel, 1988), signifying that a reduction in EMG frequency is indicative of the onset of muscular fatigue (Camic *et al.*, 2010).

Furthermore, the accumulation of muscle contraction by-products such as lactate, hydrogen ions and phosphate decrease intracellular pH and have been associated with loss of membrane excitability and a disruption in excitation-contraction coupling by impairing the release of Ca^{2+} from the sarcoplasmic reticulum (Enoka and Stuart, 1992; Moritani *et al.*, 1982). Authors have argued that a decrease in intracellular pH signals the recruitment of additional motor units to match the required work load (Moritani *et al*,. 1982), which would explain the increase in EMG amplitude observed without changes in force output during fatiguing protocols (Camic *et al.*, 2010; Petrofsky, 1979).

In summary, physiological changes along the excitation-contraction coupling processes affect muscle function at microscopic levels and can be detected through electromyography before any changes in force output are observed. A disruption in the Na^+-K^+ equilibrium affects the excitability of muscle fibre membranes, which is translated into a decrease in EMG frequency; while a decrease in intracellular pH alters the contractility of the fibres, effecting a recruitment of additional motor units which is visible through an increase in EMG amplitude (Camic *et al.*, 2010).

2.4.1 Low and High Frequency Fatigue

Peripheral muscle fatigue has been classified into two subgroups according to the duration, intensity and nature of the induced fatigue: high frequency fatigue (HFF) and low frequency fatigue (LFF). LFF is characterised by a reduction in force output in response to low frequency stimulation (10-50Hz) and by long recovery periods, ranging from several hours to a few days (Keeton and Binder-Macleod, 2006). HFF, on the other hand, involves a temporary reduction in muscle force in response to high frequency stimulation (100Hz) which subsides in minutes (Keeton and Binder-Macleod, 2006; Jones, 1996).

LFF is traditionally understood to occur in response to long duration exercise protocols with low force outputs, although more recent publications have suggested a relation to the overall magnitude of induced fatigue rather than to the duration or load implemented in the protocol (Inguchi et al., 2008; Keeton and Binder-Macleod, 2006). In other words, recent suggestions claim that a highly demanding protocol is likely to result in LFF, regardless of its duration (Inguchi et al., 2008). Muscle fibre damage, induced by eccentric work, and a disruption in the excitation-contraction coupling process, including the disruption of Ca^{2+} concentrations, are some of the proposed mechanisms that induce LFF; while the disruption in Na^{+}-K^{+} gradients, and the subsequent reduction in membrane excitability, is proposed to be more closely linked to HFF (Kyparos et al., 2012; Jones, 1996; Metzger and Fitts, 1987). LFF is therefore more likely to occur in consequence to prolonged activity, and can affect muscle function for extended periods of time, while HFF is most often observed during resistance exercise sessions and portrays rapid recovery periods.

Understanding the causes and effects of these types of fatigue enables clinicians to design training sessions more effectively for individual patients. Healthy individuals may only report discomfort and weakness following fatigue, but clinical populations may witness significant impairment of motor function, especially with LFF, affecting daily living tasks (Keeton and Binder-Macleod, 2006). This emphasises the importance of foreseeing the possible impact of an exercise protocol on fatigue, ensuring that clinical populations . Clinical populations may benefit from short exercise protocols with moderate to high loads, inducing the selective and rapidly recovering HFF, rather than long duration and/or highly demanding protocols which would induce LFF, causing the long term loss (hours/days) of low frequency force and possibly affecting daily living tasks. Furthermore, having understood the different causes of low and high frequency fatigue, an assessment of fatigue through electrical stimulation can help identify its source in clinical populations, to further aid in the diagnosis motor and/or neurological pathologies.

2.5 Estimating muscle contribution to movement

The flexion and extension of joints is brought about by the complex interaction of multiple muscles, that contribute to the movement in different proportions and directions. Currently, the most direct way of measuring muscle activity is through the use of electromyography (EMG), while two biomechanical approaches, commonly used to estimate muscle forces, are known as *forward dynamics* and *inverse dynamics*. The following sections will explore each method separately to determine their validity for the purposes of this project.

2.5.1 Electromyography

The only instrument that currently enables the direct measurement of the activity of a single muscle during movement is electromyography, which involves detecting the electrical activity of a muscle through the use of either surface or intramuscular electrodes. Surface EMG measurements are directly related to force output, although this relationship is hardly linear (De Luca, 1997). This is due to a variety of physiological and biomechanical factors that influence the contribution of muscle force to the joint’s movement, the levels of motor unit activation and the detection thereof via the electrodes (De Luca, 1997).

From a physiological perspective, the amplitude of a signal is not indicative of the amount of force produced by a contraction. Although an increase in signal amplitude is associated with an increase in motor unit recruitment and synchronization (Yao *et al.*, 2000), prompting greater contractile force, the relationship between motor unit activation and force output often produces a logarithmic curve rather than a linear relationship (Manal and Buchanan, 2003; Suzuki *et al.*, 2002; Alkner *et al.*, 2000; De Luca, 1997). Furthermore, differing force-amplitude curves have been observed for different muscles, which demonstrates the complexity of this relationship. Within the same muscle group, a more linear relationship has been documented for the vastus lateralis with respect to the vastus medialis or rectus femoris (Rodriguez-Falces *et al.*, 2015; Alkner *et al.*, 2000) and there appears to be a tendency for this relationship to be more linear in smaller muscles (De Luca, 1997). This may be related to the size of the electrode's detection volume relative to the size of the muscle: in a small muscle, the electrode detects a larger percentage of motor units and therefore gives a more accurate representation of the overall activation of the muscle; while in larger muscles, the electrode can only detect a small percentage of the active motor units which may underestimate, or overestimate, the activation of the muscle as a whole (De Luca, 1997). This remains a limitation of EMG data recorded from large muscles that can only be minimised by placing the electrode on the muscle belly in order to maximise motor unit detection (SENIAM, 2012).

Furthermore, the value of EMG amplitude recorded by the electrodes is not representative of the magnitude of contractile force exerted by the muscle. This value is dependent on a wide range of physiological factors, including skin impedance, subcutaneous adipose tissue, fibre type composition, temperature and blood flow. Skin impedance and subcutaneous adipose tissue both dampen the signal in surface electromyography (Blanc and Dimanico, 2010; De Luca, 1997). The thickness of the adipose tissue is a characteristic of the participant's body composition and cannot be controlled, however, the level of skin impedance can be reduced by shaving, thoroughly cleaning the surface of the skin and lightly abrading it in order to remove dead tissue (Blanc and Dimanico, 2009). As for muscle composition, type II muscle fibres possess a higher action potential than type I fibres, contributing to a higher EMG amplitude and frequency (Kupa *et al.*, 1995; Linssen *et al.*, 1991); type I fibres, on the other hand, possess a lower fatigability than type II fibres, which translates to lesser changes in the EMG spectrum during fatiguing tasks (Kupa *et al.*, 1995; Linssen *et al.*, 1991). EMG frequency is also altered with warm up, which is suggested to improve muscle conduction velocity due to the increased blood flow, hence increasing motor unit discharge rates and ATPase activity rates, enhancing cross-bridge cycling rate. Following regular training, these enhancements in neural and physiological activity induce an increase in mean EMG frequency, which is translated to a greater power output by the muscle (Stewart *et al.*, 2003). In addition to internal body temperature, the influence of ambient temperature on transpiration, blood distribution and, consequently, muscle conduction velocity are also reported to cause an increase in EMG frequency at higher temperatures and a decrease at lower temperatures (Petrofsky and Laymon, 2005; Madigan and Pitcoe, 2002), demonstrating a need to control environmental temperature, as well as pre-test warm up protocols, during EMG trials. In order to compensate for these limitations, electromyographic studies often normalise the amplitude signal to that of a maximal voluntary contraction (MVC), presenting values as a percentage of the peak amplitude obtained in the MVC test. This enables a better interpretation of the data and for the comparison of readings obtained between participants.

From a biomechanical perspective, the complexity of the human body implies the contribution of a number of agonist, synergist, stabilizing and antagonist muscles for joint movement in different proportions. The interaction of these muscles, the lengths of their moment arms and their action around the joint, collectively determine the direction and magnitude of joint moments. Furthermore, if the action is dynamic rather than isometric, the complexity of these variables increases considerably throughout the ROM, including changes in moment arms of both muscles and external loads, degree of overlap of contractile filaments and movement velocity. It would therefore be ingenuous to expect a direct linear relationship between the isolated contribution of a single muscle and the aggregate force output of a movement. Furthermore, the co-activation of adjacent synergist or antagonist muscles not only affects the mechanical torque output about a joint, but can also contaminate the EMG readings of the target muscle. In fact, one of the major concerns in surface EMG is the difficulty in accurately positioning the electrodes to maximise amplitude detection from the target muscle and concurrently minimise crosstalk. Crosstalk contamination has been reported to reach values of 16% the amplitude of the neighbouring muscle, or even 49% in extreme cases (De Luca *et al.*, 2012). The detection volume of the electrodes and their placement on the target muscle affect both the amplitude and frequency of the signal. The detection volume of an electrode refers to the area of the muscle from which the electrode records a signal and is determined by the distance between the two electrodes. A SENIAM report (Hermens *et al.*, 2000) documented that a substantial portion of EMG publications implemented an inter-electrode spacing of 20 mm. Upon reviewing the literature on inter-electrode distance and crosstalk, Hermens *et al.* (2000) also reported that any reduction in the spacing below 40 mm did not affect the EMG signal detection for superficial muscles, and concluded that 20 mm is an appropriate inter-electrode distance provided that the electrodes do not overlap on myotendinous junctions or innervation zones, as this would reduce the signal amplitude. Despite these recommendations, other publications reported significant evidence of crosstalk with 20 mm electrodes, proposing a need to further explore this issue (Vugt and Dijk, 2001; Mesin *et al.*, 2000). A recent investigation by De Luca *et al.* (2012) addressed the difficulty in determining the optimal inter-electrode distance, aiming to minimise crosstalk yet maximise signal detection from the target muscle. The study concluded that an inter-electrode distance of 10 mm provided the optimal balance between the two factors: at distances of 15 mm and above, the amplitude of crosstalk signals increased more rapidly than that of the target muscle; while reducing the distance to 5 mm increased the dominance of baseline noise, affecting signals from low activation tasks (De Luca *et al.*, 2012). Besides regulating the inter-electrode distance, further steps can be taken to filter out EMG signals from adjacent muscles. Crosstalk signals are normally propagated across the entire muscle and can be identified as foreign with the addition of a second electrode (Delsys, 2014). Due to the larger distance between their origin and the electrodes, cross-talk signals from neighbouring muscles possess a larger latency from the target muscle signal and can therefore be recognised as similar by adjacent surface electrodes (Delsys, 2014). With the addition of a third sensor, double differential electrodes can filter out crosstalk contamination more effectively than single differential ones (with only two electrodes) by eliminating signals that appear similar to all three sensors (Vugt and Dijk, 2001). Nonetheless, in muscles where crosstalk is not regarded as a major issue, single differential electrodes are still reported to sufficiently reduce crosstalk contamination provided that the inter-electrode distance is equal to 10 mm (De Luca *et al.*, 2012).

A small detection volume, however, also has its disadvantages. During dynamic contractions, the movement of muscle fibres with respect to the surface electrode is sufficient to place, or remove, a motor unit in the detection volume of the electrodes, thus affecting the signal (De Luca, 1997). However, given that motor units are not homogenous in size or distribution (Bodine-Fowler *et al.*, 1990), and that surface electrodes are affixed to the skin rather than the muscle itself, this element is currently not controllable through surface EMG and remains a limitation of EMG studies of movement (De Luca, 1997).

Despite the numerous limitations that define the inherent variability of surface EMG measurements, multiple studies have assessed the reproducibility of their readings, concluding that EMG is a reliable method to measure muscular activation during both isometric and dynamic contractions (Jakobsen *et al.*, 2012; Grape *et al.*, 2009; Fauth *et al.*, 2010; Alkner *et al.*, 2000; Sleivert and Wenger, 1994).

2.5.2 Forward Dynamics

Having determined the level of muscular activation through EMG, joint moments can be estimated by translating these values to rotational forces through forward dynamics. The process begins by recording muscular activation, which is normalised to MVC to obtain a number between 0 – 1 (Buchanan *et al.*, 2005). The EMG values are used to calculate muscle force output although, as mentioned, this relationship is hardly ever linear and can vary substantially between muscles (De Luca, 1997). To correct for this limitation, a Hill-type muscle model is applied, taking into account the relative length of the muscle fibre to its optimal length, pennation angle, resting tendon length and maximal force output (Manal *et al.*, 2002; Zajac, 1989). These variables are, however, not constant. The optimal fibre length for peak force output, for example, is reported to increase with lower loads (Guimaraes *et al.*, 1995); this skews the length-force relationship curve, but can be corrected mathematically (Lloyd and Besier, 2003). In addition, both the fibre length and the pennation angle, which determine the direction of force transmission in the muscle, can vary significantly between individuals (Brughelli *et al.*, 2010; Rassier *et al.*, 1999; Herzog *et al.*, 1991; Lynn and Morgan, 1994) and tendon stiffness affects internal forces exerted on the muscle fibre during contraction (Buchanan *et al.*, 2005). Another factor to take into account is the delay that exists between the EMG readings and mechanical force output, reportedly ranging between 10ms – 100ms (Buchanan *et al.*, 2005) which, as established by Buchanan *et al.* (2005) and Lloyd & Besier (2003), can be corrected by applying differential equations to the EMG data, if the degree of electromechanical delay is known for the implemented set-up.

To further optimise the non-linear EMG-force relationship, some authors have recorded a range of muscle activation and force outputs prior to testing, correlating them to produce a more accurate curve for the specific test subject (Manal *et al.*, 2002). These values, however, remain constrained to the fact that external momentum is the result of the cumulative action of multiple muscles and cannot offer an accurate representation of the EMG-force relationship of a specific muscle and, therefore, results in an optimization matrix that includes EMG-to-activation coefficients of all muscles involved (Manal *et al.*, 2002). Finally, muscle force is translated to joint moment through forward dynamics by including estimated values of moment arms, limb length and mass, although the individuality of human anatomy further adds to the approximation of such calculations. These lengths are most often taken from anatomical studies that offer a mean value of a population sample and may not be representative of the participant being tested. Although this is currently the most applicable method available for estimating joint moments from EMG readings, it involves a series of complex calculations with numerous variables and estimations, and the results should therefore be considered with some caution. Variations of this process have been used to produce a real-time EMG-driven virtual arm (Manal *et al.*, 2005), to estimate the contribution of muscle and soft tissue loading during leg exercises (Lloyd and Besier, 2003; Lloyd and Buchanan, 1996) and to produce computerised models of human kinematics (Ghafari *et al.*, 2009; Koehle and Hull, 2007; Stelzer and Stryk, 2006), all with varying, yet acceptable, degrees of accuracy. Forward dynamics is a valuable method for its applications in biomechanical technology but, due to the high variability of anatomical measurements that exists between individuals, it is not currently appropriate for an exact analysis of muscle forces involved in movement.

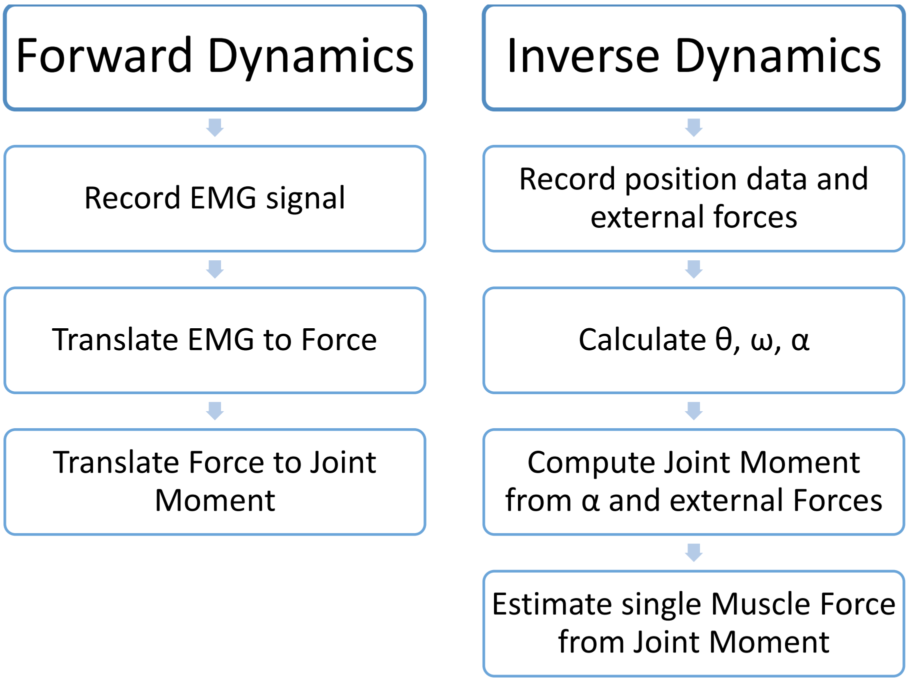


Figure 2.4 – Schematic summary of the main steps involved in Forward and Inverse Dynamics calculations.

2.5.3 Inverse Dynamics

While forward dynamics work from muscle to movement, estimating applied forces from EMG measurements (Figure 2.4), inverse dynamics work from movement to muscle, estimating the contribution of each muscle based on externally measured joint movements and applied forces (Buchanan *et al.*, 2005). The process begins with recording the position of tracking targets placed on the subject’s limbs, from which joint angles, angular velocities and angular acceleration are then computed. Newton-Euler equations are then used to compute the joint moments based on segmental data and known applied forces (Cleather and Bull, 2010), while Lagrangian equations are often implemented to constrain the calculations to biomechanical parameters of motion (Moreira *et al.*, 2013). The final output of these calculations gives an estimation of total joint moment based on kinematic data and, if musculoskeletal geometry is included, further calculations could be used to extrapolate the force applied by each muscle acting around the joint. Each step of the process involves complex, non-linear relationships with multiple variables that add to the uncertainty of the results. The limitations of this process are already present in its early stages: during the collection of positional parameters. Thanks to the advancement of motion capture technology, 3D models can be produced based on the location of retroreflective markers with an accurate representation of their true location to less than 0.2 mm for small volume analyses (Berlander, 2012). Despite the accuracy of the system, however, markers are subject to skin movement artefact, which consists of the movement of the skin relative to the underlying bones, reportedly ranging between 10-30 mm and translating to up to 8° in joint angle errors in the lower and upper limbs (Roux *et al.*, 2002; Cappozzo *et al.*, 1996). Errors in joint angles, combined with possible inaccuracies in marker locations due to noise in the motion capture systems, can translate to relatively large errors in segmental angular velocity and acceleration, and have been documented to be the main contributors to inaccuracies in joint moments estimated through inverse dynamics (Riemer *et al.*, 2007).

The estimation of individual muscle forces through inverse dynamics presents the greatest challenges. Primarily, the proportion with which each muscle contributes to a joint's movement cannot be calculated without a direct measure of their activation, leaving for a range of possible combinations to be computed. Furthermore, agonist-antagonist coactivation would be masked in inverse dynamics. The calculations offer a net value specifying the opposing forces exerted by two antagonising muscles and, without a direct measure of the antagonist's involvement, its contribution cannot be accounted for (Aagaard *et al.*, 2000). Yet, even if EMG recordings were to be included in the calculations, the lack of a linear EMG-force relationship would still provide inaccurate results. Finally, an accurate model of muscle geometry is required in order to compute the force exerted by each individual muscle around the joint. These measurements are highly individualistic yet must be based on averages from cadaveric anatomical studies, which may not necessarily represent the subject being tested. Furthermore, the model must account for changes in the length and moment arms of the musculotendon units throughout the ROM (Buchanan *et al.*, 2005), which presents yet another challenge.

In order to overcome the many limitations of forward and inverse dynamics, Buchanan *et al.* (2005) and Lloyd & Besier (2003) have developed models that integrate both methods. The models consisted in the recording of movement kinematics as well as measuring varying degrees of force output for all muscles acting around the joint and correlating them to EMG readings. The recordings were used to calculate joint moment through a combination of forward and inverse dynamics, and were compared to experimental joint moments measured via dynamometry. Both authors determined that the results from the forward and inverse dynamics calculations could be mathematically compared to each other, after adjusting the model parameters until the error between the two results was minimised. The calibrated models could then be used to predict joint moments and single muscle force for a given participant during movement with good accuracy (Buchanan *et al.*, 2005) even with trials being performed two weeks apart (Lloyd and Besier, 2003). This model, however, required a long calibration process and an abundance of experimental data to be gathered before it could be used to accurately estimate muscle force during movement. Inverse dynamics are, therefore, useful for estimating joint moments if accurate positional data is provided, but are not appropriate for estimating the force applied by a single muscle.

2.5.4 Method choice

The greatest limitation of both forward and inverse dynamics appears to be the inaccuracy in calculating force output for specific muscles. The focus of this thesis is to compare magnitudes and patterns of activation of specific muscles throughout the ROM, extrapolating the findings to predict outcomes in architectural and performance adaptations. For these purposes, an analysis focused on experimental measures of muscular activation through EMG was deemed more appropriate than an indirect measure of resultant forces on joint moments.

2.6 Elastic resistance training

Several articles have investigated the effects of exercising with elastic resistance compared to isotonic resistance (free weights, pulley machines), although there does not appear to be a consensus regarding the electromyographic responses or strength adaptations that occur as a result of elastic resistance exercise. This section will explore the findings reported in publications on elastic resistance to date, including electromyographic responses, strength adaptations and applications in clinical settings.

2.6.1 A history of elastic training

In 1897 Whitely Co., (Chicago, USA) commercialised the Whitely Exerciser, a complex system of pulleys, coils and elastic ropes promoted as "*the standard exercising apparatus of the World*" (Figure 2.5) . Thereafter, several variations of the contraption began to emerge from different brands, such as "Sandow's Own Combined Developer" which included the addition of metallic coils and small dumbbells instead of handles (Chapman, 1994). Throughout the 20th century, technological advances and creative minds brought in the use of surgical tubing, bicycle inner tubing and other elastic materials to add variation to exercise regimes. Finally, in 1978 two physical therapists found a way to commercialise Dental Dam (an elastic sheet used to protect the mouth during dental interventions) as a material specifically tailored to physical exercise: Thera-Band® was born (Page and Ellenbecker, 2003).

Despite their debatable claim to have "invented and pioneered the use of elastic resistance products" (Theraband, 2017), Thera-Band® have certainly commercialised the industry of elastic training, creating a product that was cheap, versatile and widely available. Adding bright colours to code resistance levels and producing the material in different shapes and forms boosted sales, ushering the product into physiotherapy clinics, gyms and homes. As a result, elastic training was swiftly embraced by physiotherapists due to their light resistance and to the gradual increase of load that the elastic material offered. The very first scientific article to mention the use of elastic bands deemed them safe for geriatric patients (Aniansson *et al.*, 1984) and, henceforth, scientific publications began supporting the use of elastic materials in rehabilitation settings (Andersen *et al.*, 2010; 2011) with the generic assumption that elastic resistance was only applicable in light training contexts (Ebben and Jensen, 2002; Simoneau *et al.*, 2001), or in Schwarzenegger's words: "*some kind of exercise device with rubber bands or springs or whatever is a lot better than doing nothing*" (Schwarzenegger & Dobbins, 1998, pg.72).

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Figure 2.5 – Whitely Exerciser advertisements from 1897 (top), 1899 (bottom left) and 1900 (right) (Amazon.com).

The legendary bodybuilder's words give a sense of the general attitude towards elastic resistance in the sporting world, but the frustration of some authors towards this misconception led to research investigating whether elastic resistance could be effectively applied to high intensity strength training, demonstrating that, despite an apparently lower external load, elastic training induced equal levels of stress, markers of muscle damage and hormonal responses to weight training (Aboodarda *et al.*, 2011; 2012), concluding that "*elastic training is an acceptable exercise device for high intensity resistance training in the final stages of rehabilitation as well as athletic conditioning*" (Aboodarda *et al.*, 2012, pg. 2). Today, elastic materials are re-emerging as the method of choice in physiotherapy and are making their way into the athletic world, finding their place in home-based fitness training as well as high performance settings.

2.6.2 Material Properties of Thera-Band® elastic tubing

Thera-Band® is currently among the leading brands in the provision of elastic materials for physical exercise. Due to the consistency of their materials, and available information on material properties of the product, the use of Thera-Band's elastic tubes was implemented in all studies of this project (Santos *et al.*, 2009; Patterson *et al.*, 2001; Simoneau *et al.*, 2001; Page *et al.*, 2000).

Elastomers are characterised by a progressive increase in applied load with elongation, an increase of their resistance at higher strain rates and a relatively short durability and loss of elasticity with usage (Young and Lovell, 1991). Mechanical studies of the material properties of Thera-Band® elastic tubing have established that their resistive force increases with elongation, where stiffer tubes increase resistance at higher rates (Figure 2.6) (Santos *et al.*, 2009). In addition, Barry and Wood (2015) reported that the average increment in resistance between available Thera-Band® colours is of 11.9%, facilitating the transition between band colours in resistance training. A table of equivalent weights (Table 3.2), based on regression equations for resistances provided by each tube at different percentages of elongation, is also provided and endorsed by the manufacturer (Page *et al.*, 2000).

In their study on evaluating the material properties of Thera-Band® tubing, Patterson *et al.* (2001) found no effect of strain rates (67 %·min^{-1} to 667 %·min^{-1}) on stiffness of the materials, indicating that these elastic tubes do not present significant changes in resistance in relation to the speed of elongation and therefore should not affect loading during exercise at high velocities. In the same study, Patterson *et al.* (2001) found that cyclic loading of up to 5,800 stretch cycles from 100% to 200% stretch at 1Hz did not significantly affect the material properties of Thera-Band® tubes, indicating that the material is appropriate for sustained use throughout a prolonged training programme, provided that it is kept away from extreme temperatures and dry environments.

The use of elastic tubes is becoming increasingly prevalent in both rehabilitation and performance settings (Jakobsen *et al.*, 2014; Aboodarda *et al.*, 2012; Andersen *et al.*, 2010) and, although several authors have quantified the applied load of elastic resistance in kg (Santos *et al.*, 2009; Barry and Woods, 2015; Page *et al.*, 2000), the application of comparative loads on muscular responses has not been sufficiently validated through physiological observations. The following sections will therefore explore the current literature on muscular responses to exercising with elastic resistance.

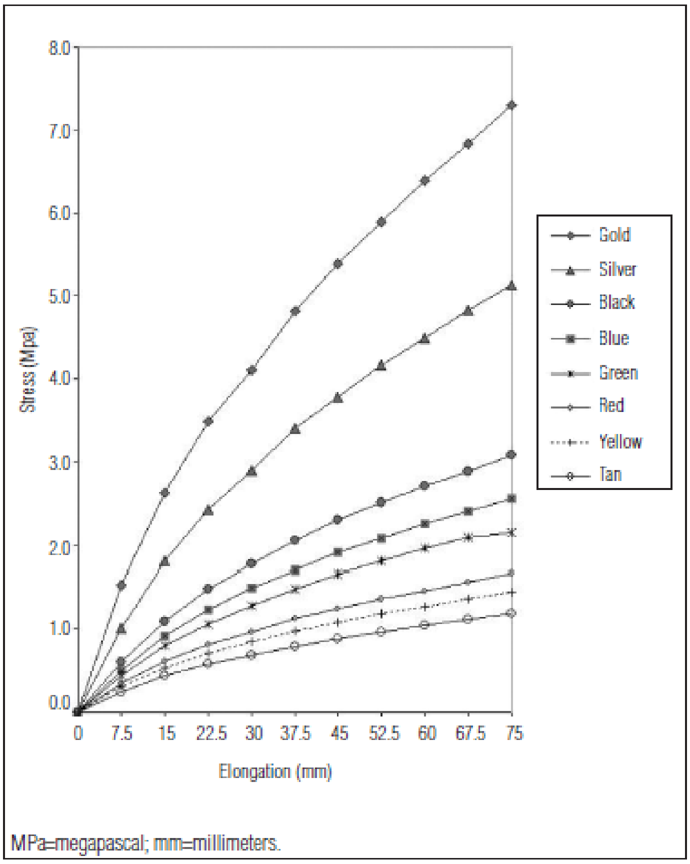

Figure 2.6 - Stress curves for each level of available Thera-Band® tubing (Santos et al., 2009)

2.6.3 Muscular activation responses to elastic and weighted resistance training

Elastic resistance can elicit magnitudes of peak activation of the agonist muscles similar to those elicited with weight resistance or gym machines during leg extensions (Jakobsen *et al.*, 2013; Matheson *et al.*, 2001; Aboodarda *et al.*, 2011), leg curls (Jakobsen *et al.*, 2014), hip abductions (Serner *et al.*, 2014), lateral raises (Andersen *et al.*, 2010) and bicep curls (Aboodarda *et al.*, 2013). However, some studies reported a higher activation of agonist muscles under elastic resistance during hip abductions (Brandt *et al.*, 2013) and abdominal crunches (Sundstrup *et al.*, 2012). Aboodarda *et al.* (2011) reported equal levels of vastus lateralis activation during a leg extension under elastic and weight resistance, despite a lower measure of applied force in the elastic condition. The authors attributed this difference to the variable nature of elastic resistance, which requires greater movement control than conventional gym machines or free weights. Considering that the vastus lateralis contributes to the stabilization of rotational knee movements, it is highly likely that it would have become more engaged to provide movement stability under a variable resistance.

Furthermore, variations in the exercise set-up between elastic and weight conditions can contribute significantly to the differences in the recruitment of primary and secondary muscles between the two conditions. For example, in a study by Sundstrup *et al.* (2014), who compared lunges with hand-held dumbbells to lunges with an elastic band looped around the shoulder and front foot, the two conditions presented strong biomechanical differences which would have determined any alterations in muscle activation. In their study, the elastic bands caused an anterior pull on the trunk, reducing the load placed on the knee extensors and placing it on the posterior kinetic chain muscles, requiring a greater engagement of postural and stabilizer muscles such as the glutei, erector spinae and hamstrings with respect to the weight condition. Accordingly, a greater activation of core, synergist and stabilizer muscles with elastic resistance has been reported by various authors, leading to the argument that elastic training may be more appropriate than weights for proprioceptive training (Vinstrup *et al.*, 2015; Sundstrup *et al.*, 2014; Jakobsen *et al.*, 2013; Brandt *et al.*, 2013; Lister *et al.*, 2007; Schulties *et al.,* 1998). Contrastingly, however, some studies reported no difference in secondary muscle activation between the two resistance methods, indicating that the effects of elastic resistance on muscular responses may be more complex than initially anticipated (Serner *et al.*, 2014; Sundstrup *et al.*, 2012; Witt *et al.*, 2011; Matheson *et al.*, 2001). The difference in these findings may, therefore, be related to the nature of the exercises selected in the studies and the consequential differences in direction of applied load throughout the movement. Aside from its provision of an increasing load (Santos *et al.*, 2009), the variability of elastic resistance is also caused by the mutable direction of its applied load, which is relative to the anchoring point of the elastic tubes and thus varies throughout the range of motion. Considering the complex system of levers that exists in the biomechanics of movement, a force with variable direction is expected to significantly affect patterns in muscular activation and muscle recruitment in order to maintain stability in the joints involved.

Finally, the physical differences between mass (dependent on gravity) and elastic tension (dependent on its anchoring point), emphasize the importance of considering exercise set-up and direction of force application when comparing the two resistance methods. A study by Simoneau *et al.* (2001) clearly illustrates this issue, where the authors report opposing curves of applied resistance when participants performed an elbow flexion while laying supine either with dumbbells or with elastic tubes anchored below their feet. The obvious differences in direction of applied load were responsible for the differences in its magnitude throughout the ROM. A contrasting finding is observed in a study by Saeterbakken *et al.* (2014), who reported no differences in core muscle activation during squats when substituting part of the barbell weight load with vertical elastic bands (hence maintaining the direction of applied load in line with gravity). Based on these observations, it can be hypothesised that the differences in muscular activation levels reported in the literature can be attributed to the difficulty in comparing variable resistance methods to isotonic ones, stressing the need to fully understand muscular activation responses under elastic resistance through a more comprehensive investigation of its patterns.

Furthermore, very different methods of data collection were implemented among the mentioned studies, where some only collected measures of applied force (Simoneau *et al.*, 2001) and others measured muscular activation via EMG (Saeterbakken *et al.* 2014), making it difficult to compare their findings. As described in Section 2.5, measures of external applied forces do not necessarily reflect the contribution of each muscle to a movement. Therefore, a comparison of muscular activity elicited by different resistance methods would be best performed through the use of EMG.

Although most of the mentioned studies on elastic training did implement EMG, they also reported muscular activation in terms of total, mean or peak EMG, while specific patterns of muscular activation throughout the full range of movement have been scarcely considered. By reporting muscular activation as single values, the order of recruitment, the rate of force development [1]and the length at which the muscle is activated cannot be investigated. Considering that these variables pose strong implications for both neuromuscular and architectural adaptations, the specificity of muscular activation throughout the ROM should be investigated when comparing resistance methods. The few studies that did consider muscular activation throughout the ROM reported that elastic resistance elicited a higher muscular activation than weight resistance at the end of the concentric phase during hamstring exercises and bicep curls (Jakobsen *et al.* 2014; Aboodarda *et al.* 2013). These responses are produced by the mechanical properties of elastic materials that apply higher resistance when stretched (Santos el at., 2009; Simoneau *et al.*, 2001) and have led several authors to suggest that that a combination of weights and elastic tubes may provide more effective strength and power training programmes than using one method alone, by exerting the muscle throughout the range of motion, hence maximising strength adaptations (Aboodarda *et al.*, 2011; Frost *et al.*, 2010; Wallace *et al.*, 2006; Behm, 1991), although this claim is yet to be verified.

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[1] Throughout this thesis, “*rate of force development*” refers to the speed at which a muscle reaches peak force output, as defined by the slope of the EMG curve from the moment of activation to peak amplitude.

Therefore, due to the difficulty in comparing variable resistances with isotonic ones, the reported findings on muscular activations during elastic resistance exercise are, in some cases, highly contradictory. While elastic resistance can effectively elicit similar magnitudes of muscular activation to weight resistance, patterns in activation throughout the ROM can differ substantially; and while some studies suggest a tendency for greater auxiliary muscle recruitment under elastic resistance, other studies contradict this statement. The lack of consensus in the literature portrays the need for further investigation of neuromuscular responses during elastic resistance exercise in order to promote the effective designing of exercise programmes with this method of resistance.

2.6.4 Elastic training in rehabilitation settings

The versatility of elastic materials has rendered them attractive for clinical settings, where the possibility of applying very light loads in any direction have made them a suitable instrument for special populations. Following the very first scientific publication on elastic resistance training, which investigated its use in geriatric patients (Aniansson *et al.*, 1984), elastic training has been widely recommended for its use in rehabilitation settings, demonstrating the feasibility and effectiveness of elastic based exercise programmes for the elderly (Chen *et al.*, 2015; Yasuda *et al.*, 2014; Chen *et al.*, 2013); for pulmonary and cardiovascular disease patients (Nyberg *et al.*, 2014; Qi *et al.*, 2014; Ramos *et al*, 2014) and for the rehabilitation of muscle injuries (Andersen *et al.*, 2010; 2011), independently of gender, age or pain levels (Jakobsen *et al.*, 2014; Sundstrup *et al.*, 2014). Findings in clinical settings include improved neuromuscular function (Han and Ricard, 2011), strengthening of injured or painful muscles (Mortensen *et al.*, 2014; Andersen *et al.*, 2011) and improved strength and flexibility in the elderly (Colado and Triplett, 2008). Elastic training has been therefore considered an appropriate method for muscular rehabilitation due to its application of a progressive load as opposed to the abrupt change in muscular activation often observed with weight resistance (Yasuda *et al.*, 2014; Hodges and Kriellaars, 2013; Han and Richard, 2011).

2.6.5 Adaptations to elastic training in heathy populations

Very few studies have, however, investigated the effectiveness of elastic resistance training on muscular adaptations for performance in healthy populations. The first intervention study to be published on this subject reported increases in 1 repetition maximum (1RM), repetitions to failure and type IIAB fibre proportion in the lower limbs of both men and women following 8 weeks of resistance training with the elastic "Sport Chord" (Hostler *et al.*, 2001). The study demonstrated that elastic training is an effective method for improving strength endurance in the lower limbs, although it did not report the number of repetitions used in the training protocol, nor the equivalent intensity of the tubes, rendering it difficult to use this study for comparison with literature on weight training. Cronin *et al.* (2003) later considered both EMG patterns and strength adaptations following jump squats performed on a supine squat machine with or without the addition of elastic resistance. The group exercising with the combined elastic-weight resistance improved lunge performance more than the weights group. The added improvement in the combined condition was attributed to an increased eccentric activity due to the recoil force exerted during the braking phase after landing from the jump squat, indicating that elastic resistance provided an added eccentric load on the quadriceps muscles, mediating an increase in strength gains. It must however be noted that the kinematics of a jump squat differ substantially from single joint exercises such as a bicep curl or leg extension, and these findings may not be transferrable to all training contexts.

More recently, two studies examined the effects of combining elastic and weight resistance training during bench presses in trained (Anderson *et al.*, 2008) and untrained individuals (Bellar *et al.*, 2011). The former study substituted 20% of the load with elastic tension, while the latter substituted 15% of load with elastic tension, and both studies observed a significantly greater increase in 1RM in the combined condition group. The authors concluded that combining elastic and weight resistance effectively enhanced strength adaptations, attributing the difference to the variable resistance that elastic tension offers, eliciting an increased muscular overload at joint angles that are normally more advantageous during weight resistance.

Finally, in a study on neural and hormonal responses to elastic training, Aboodarda *et al.* (2011; 2012) found that by decreasing the initial length of the tubes by 30% and adding multiple tubes in parallel, sufficient resistance was achieved in order to produce similar neuromuscular and anabolic responses to high intensity weight training. The authors concluded that elastic resistance is an acceptable form for high intensity resistance training and suggested that elastic and weight training may elicit similar long term training adaptations, although intervention studies are yet to explore the outcomes of exercising with elastic resistance alone for healthy populations. A more comprehensive comparison of muscular adaptations produced by training with elastic, weight or combined resistances, including adaptations at specific joint angles, would offer a better understanding of the effects of either method on performance, aiding professionals in their selection of resistance methods for their specific contexts.

2.7 Summary

Despite the increasing popularity of elastic resistance in all aspects of rehabilitation and performance, there is still paucity of research investigating the specific patterns of muscular activation responses and adaptations during elastic resistance exercise. There is little consensus in the literature regarding muscle recruitment and very few studies have addressed patterns of muscular activation throughout the range of motion. Understanding the differences in muscle recruitment during elastic resistance in comparison to weight resistance exercise would help determine the efficacy and applicability of either method to different aspects of resistance training such as rehabilitation, power or proprioceptive training. Furthermore, identifying specific patterns of muscular activation throughout the range of motion would help predict long term adaptations of muscle fibre architecture, further elucidating the applicability of elastic resistance training and its long term implications. Therefore, the purpose of this thesis is to provide a better understanding of the differences in muscular activation patterns elicited by elastic and weight resistance, thus helping professionals better identify the appropriate application of either resistance method in rehabilitation and strength training programmes.

General Methods

3.1 Introduction

The present chapter contains an extensive description of experimental procedures that are relevant to most studies contained in the thesis. Descriptions of equipment, exercise set up and reliability tests are contained in this section, while specific experimental protocols pertinent to individual studies are detailed in the respective chapters.

3.2 Participants

3.2.1 Recruitment

A total of 59 participants took part in one or more of the studies contained within this thesis, as reported in Anthropometric measurements

Mass (kg), stature (cm) and limb length (cm) were measured for all participants. Anthropometric measurements were taken through palpation and observation, with unclothed limbs. Leg length (A) was measured as the distance between the greater trochanter to the lateral malleolus with the participant standing upright; shaft length (B) was measured from the lateral epicondyle of the femur to the lateral malleolus; arm length (C) was measured from the acromion to the ulnar styloid process and forearm length (D) was measured from the olecranon to the ulnar styloid process (Figure 3.1). All tests were performed for the dominant limb only, which was determined by asking the participant which limb they normally used to write or to kick a ball.

Table 3.1. They were all aged between 18-40 years old, were healthy and led a moderately active lifestyle (engaged in at least 2 days of non-strenuous sport per week, but did not have an active lifestyle). Participants with musculoskeletal injuries or disorders, or any other respiratory, cardiac or neurological condition, were excluded from the study. All individuals signed an informed consent and PAR-Q forms (Appendix A) prior to participation. All studies were previously approved by Kingston University's ethic committee in line with the declaration of Helsinki.

3.2.2 Anthropometric measurements

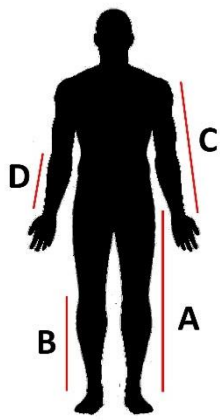


Figure 3.1 – Anthropometric measurements taken for each participant.

Mass (kg), stature (cm) and limb length (cm) were measured for all participants. Anthropometric measurements were taken through palpation and observation, with unclothed limbs. Leg length (A) was measured as the distance between the greater trochanter to the lateral malleolus with the participant standing upright; shaft length (B) was measured from the lateral epicondyle of the femur to the lateral malleolus; arm length (C) was measured from the acromion to the ulnar styloid process and forearm length (D) was measured from the olecranon to the ulnar styloid process (Figure 3.1). All tests were performed for the dominant limb only, which was determined by asking the participant which limb they normally used to write or to kick a ball.

Table 3.1 – Number of participants taking part in each study contained in this thesis

PARTICIPANT	ST. 1	ST. 2	ST. 3	ST. 4	ST. 5
1	X	X			
2	X	X	X	X	
3	X				
4	X	X	X	X	
5	X				
6	X				
7	X	X			
8	X	X			
9	X				
10	X				
11	X	X	X	X	
12	X				
13	X				
14	X				
15	X				
16	X	X			
17	X	X	X	X	
18		X			
19		X			X
20		X			
21		X			
22		X			X
23		X			
24		X			
25		X			
26		X			
27		X	X	X	
39					X
40					X
41					X
42					X
43					X
45					X
46					X
47					X
48					X
49					X
50					X
51					X
52					X
53					X
54					X
55					X
56					X
57					X
58					X
59					X

28	X	X	X	
29	X			
30	X			
31	X			X
32	X			
33	X	X	X	
34	X	X	X	
35	X	X	X	
36	X			X
37	X	X	X	
38	X			X

3.3 Equipment and procedures

This section provides a description of the exercises and conditions used throughout the project. Resistances and movement velocities used in each study are specified in the respective chapters. All exercises in the analytical studies were performed unilaterally with the dominant limb only.

3.3.1 Exercise execution

Each exercise was performed with both Thera-Band® tubing and free weights.

3.3.1.1 Bicep Curl

The elastic tube was held with a handle provided by the manufacturer and was stepped onto with the shoes to provide an anchor. A 6kg dumbbell was provided for the weighted condition. Participants were asked to stand straight, facing forward with feet shoulder width apart. The starting position of the exercise consisted in leaving the arm relaxed to the side of the body with the palm of the hand facing forward, the wrist would not turn at any point during the exercise. Participants were also asked to maintain the elbow in line with the anterior superior iliac spine (hips) through the entire execution of the exercise. Participants were asked to move through their entire ROM, the initial point being a straight arm and the final point being a flexed arm with the hand close to the shoulder and humerus in vertical alignment.

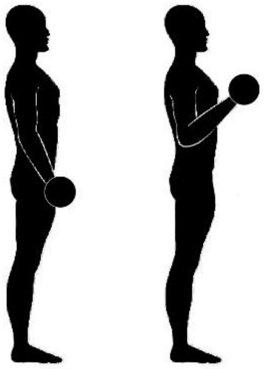


Figure 3.2 - Execution of the bicep curl

3.3.1.2 *Lateral raise Execution*

Tube attachments at the hand and floor were the same as for the bicep curls. A 1.8kg dumbbell was provided for the weighted condition. Participants were asked to stand straight, facing forward with feet shoulder width apart. They began the exercise with a straight arm and the palm of the hand facing inwards, the arm was then raised until vertical above the head, while maintaining the elbow straight and without turning the wrist.

Figure 3.3- Execution of the lateral raise

3.3.1.3 *Leg Extension Execution*

For the elastic condition, the tube was tied to l an an base of the back leg of the chair on the other end. A 6kg ankle weight was used for the weight condition. Participants were seated with their feet not touching the ground. Full ROM consisted in starting with a 90° flexion at the hip and 70° flexion at the knee to a full knee extension (180°). Seating height was adjusted per participant to ensure that the foot did not touch the ground when the knee was flexed at 90°.

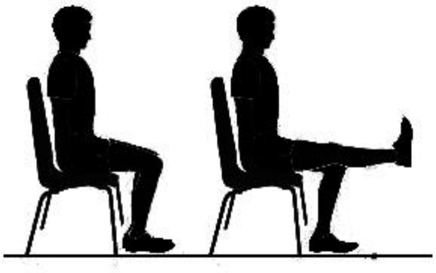


Figure 3.4 - Execution of the leg extension

3.3.1.4 Leg Curl Execution

The elastic tube was attached to an ankle strap via a hook, and was stepped over with the foot at the ground. A 2.3kg ankle weight was used for weight resistance. Participants were asked to stand straight, facing forward with knees together and hands resting on a chair in front of them. Full ROM consisted in starting with the exercising leg flexed at 120° to a full flexion of the knee.

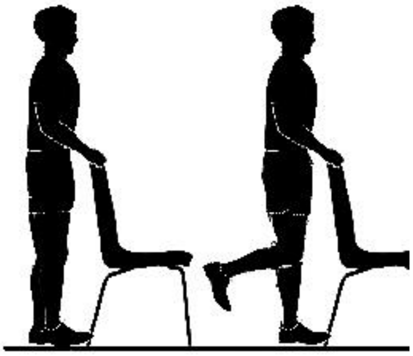


Figure 3.5 - Execution of the leg curl

3.3.2 Movement velocity

3.3.2.1 *Velocity Control*

In a study on movement strategy during shoulder exercises with elastic resistance, Hodges and Kriellaars (2013) noted that, while cadence may be specified as a form of speed control, it does not necessarily control accelerations throughout the range of motion (ROM), leading to irregular muscle activation patterns. In order to avoid these irregularities within this project, participants were asked to mirror a video showing the exercises performed at a constant speed of 60, 120 or 180 deg·s^{-1} (Figure 3.6). The video was made by filming one repetition and looping the same segment in order to maintain consistency and minimize human error. Participants were given time to become accustomed to the speed of the action required by mimicking the video a number of times without resistance before recording data. Angular velocity, analysed through 3D motion analysis, showed little variance between participants (Table 3.2), with minimal oscillation in movement velocity throughout the ROM (Figure 3.7), demonstrating that this was an effective method of controlling speed. Further statistical tests on reliability of this data is described in Section 3.3.2.3.

Figure 3.6 – Screen shot of the video used to control velocity during trials.

3.3.2.2 *Velocity selection*

A low to moderate velocity (60deg·s^{-1}) was chosen for Study 1, which is considered an acceptable training velocity for producing strength adaptations (ACSM, 2002). The specified velocity is rather slow and is more reflective of rehabilitation context than performance exercise. It was selected for three reasons: for comparability with previous studies of similar methodologies, which all used 60deg·s^{-1} as their mean angular velocity (Jakobsen *et al.*, 2014, 2012; Aboodarda *et al.*, 2013, 2011); to minimise the impact of momentum throughout the movement, hence obtaining a pattern of muscular activation that was primarily determined by the type of resistance used (elastic vs weight) rather than inertial forces; and finally to minimise the variance in EMG readings which are susceptible to time delay and motion artefact at high movement velocities (De Luca, 1997).

After analysing the impact of angular velocity on muscular activation patterns in Chapter 5, for the purpose of ecological validity, it was deemed appropriate to perform the following analytical studies at a velocity that reflected one commonly used during self-paced exercise. By doing so, the following studies would give better insight to muscular responses that occur during real life scenarios, improving their ecological validity hence making them more applicable for exercise prescriptions. During a pilot test, participants were instructed to perform three repetitions of bicep curls and leg extensions at a self-paced velocity they would normally use when training at the gym (T-SPV, W-SPV) without any visual or audio queues. Angular velocity was then measured for all controlled and non-controlled conditions through 3D motion analysis and recorded for every 20° of ROM for the bicep curl and the leg extension (Figure 3.7); the true mean angular velocity was then calculated per participant as the average of those values throughout the entire ROM (Table 3.2). After completing Study 2, which investigated the impact of three training velocities (60, 120 or 180deg·s^{-1}) on muscular activation patterns, 120deg·s^{-1} was chosen for the subsequent analytical studies (Table 3.2) as the most similar experimental velocity to the self-paced velocities ($R \geq .93$).

Table 3.2 – Mean ± SD (n=10) measured angular velocity for each experimental condition used in Chapter 5, where angular velocity was controlled (60, 120, 180), and one trial of self-paced velocity without any form of velocity control (SPV).

	60	**120**	**180**	**SPV**
BICEP CURL T (deg·s^{-1})	64 ± 10	119 ± 26	171 ± 27	111 ± 37
BICEP CURL W (deg·s^{-1})	62 ± 6	113 ± 15	150 ± 17	100 ± 28
LEG EXTENSION T (deg·s^{-1})	45 ± 5	99 ± 20	137 ± 28	95 ± 43
LEG EXTENTION W (deg·s^{-1})	50 ± 9	94 ± 17	125 ± 24	115 ± 28

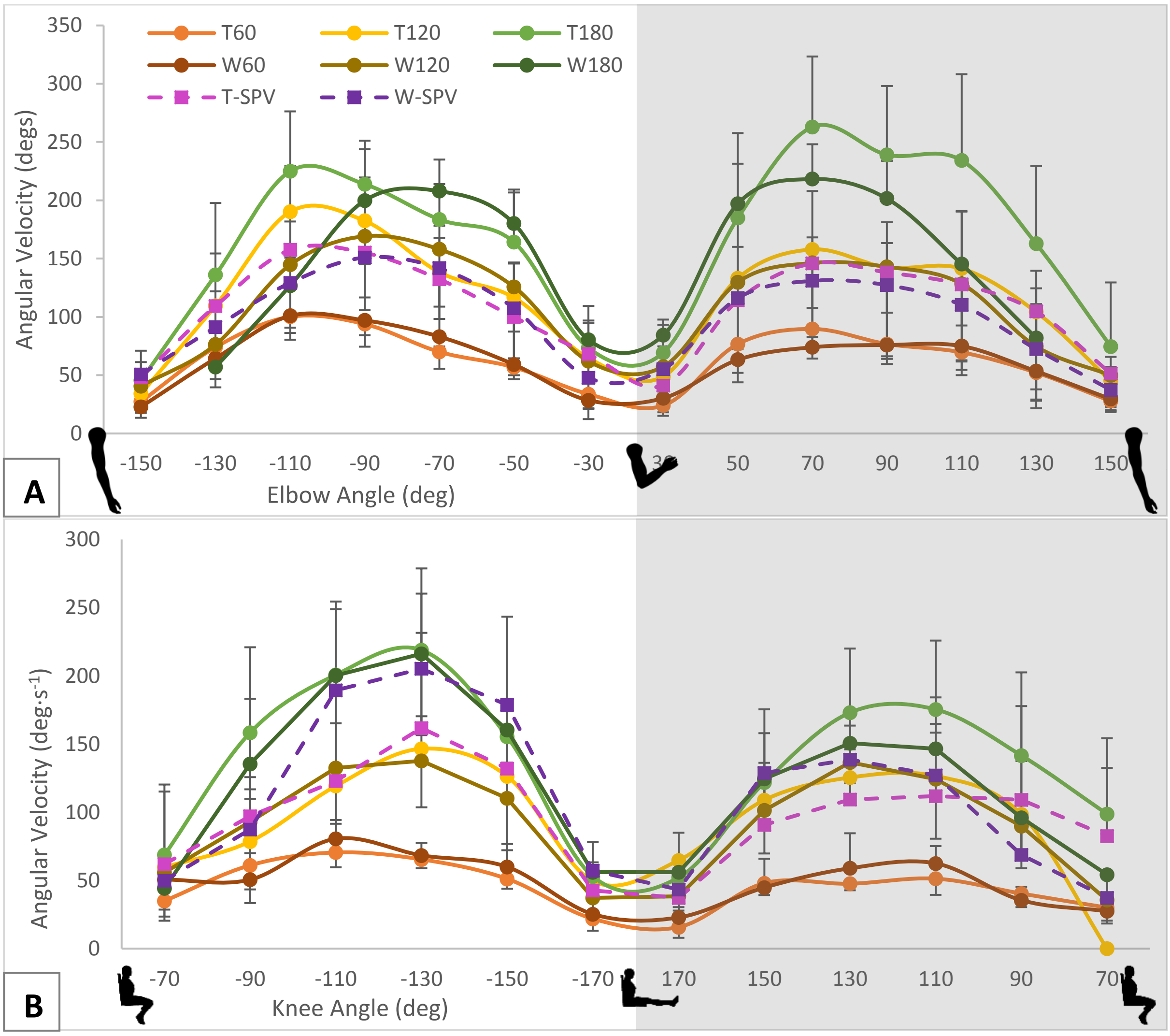


Figure 3.7 - Mean angular velocity (n=10) per every 20° of ROM, throughout the entire range of motion of (A) a bicep curl and (B) a leg extension at movement velocities 60, 120, 180deg·s^{-1} and self-selected velocity, between two resistance methods (elastic tubes and free weights).

3.3.2.3 Reproducibility of Movement velocity

Movement velocities used throughout the project were 60, 120 or 180 deg·s^{-1}. The effectiveness of using a video to control for velocity throughout the movement (Section 3.3.1) was addressed by calculating the Pearson Correlation between conditions of the same velocities under different resistances. Table 3.3 reveals a very strong correlation (R≥.88) between conditions of the same velocities under different resistance methods, and an equally strong correlation between T120, W120 and the self-paced velocity (T-SPV, W-SPV), supporting the choice 120 deg·s^{-1} as the movement velocity for studies subsequent to Study 2.

Table 3.3 – Pearson Correlation (R) of the measured mean angular velocity between elastic and weight resistances.

	BICEP CURL	**LEG EXTENSION**
T60 – W60	.97	.95
T120 – W120	.93	.97
T180 – W180	.88	.96
T-SPV – W-SPV	.97	.90
T120 – T-SPV	.96	.95
W120 – W-SPV	.99	.93

3.3.3 Resistances

3.3.3.1 Elastic resistance

Thera-Band® elastic tubing was used throughout the project. Silver tubing (high resistance) was used for the bicep curl and the leg extension, green tubing (medium resistance) was used for the standing leg curl and red (low resistance) was used for the lateral raise. The resistive force of the tubes was quantified in a study by Page *et al.*, (2000) and cited by the manufacturer in their official manuals (Table 3.4). According to these specifications, green tubing corresponds to the range of weight load between 0.9 and 4.4 kg, red corresponds to 0.7 to 3.2 kg and silver tubing corresponds to 2.3 to 11.5 kg in resistance. The author recognises the limitations of using a same load for all participants; however, due to the limited availability of resistance levels offered by the manufacturer, and to the complexity of elastic loading during dynamic exercise, it was opted to implement the same material throughout the study for consistency. One tube colour for all participants was therefore chosen considering a resistance that would allow all participants, of similar fitness level lifestyle (engaged in at least 2 days of non-strenuous sport per week, but did not have an active lifestyle), to complete the full ROM of each exercise. For the weight equivalents (W), given that all exercises stretched the tubes to more than 100% initial length, the equivalent in kilograms for 100% elongation was chosen for this study; therefore 1.8 kg were used as an equivalent for the red tube, 2.3 kg for the green tube and 6.0kg for the silver tube. The third analytical study in this project (Chapter 6) included a combined condition, where the applied load was produced by half weight and half elastic resistance: using 2.8 kg weight and a blue Thera-Band® tube at the same time.

Table 3.4 – Equivalent resistances in kg of Thera-Band® tubing as described by the manufacturer's manual, as of 2014 (Page et al., 2000)

% elongation	RED	GREEN	BLUE	SILVER
25%	0.7	0.9	1.3	2.3
50%	1.2	1.5	2.1	3.9
75%	1.5	1.9	2.7	5.0
100%	1.8	2.3	3.2	6.0
125%	2.0	2.6	3.7	6.9
150%	2.2	3.0	4.1	7.8

175%	2.5	3.3	4.6	8.6
200%	2.7	3.6	5.0	9.5
225%	2.9	4.0	5.5	10.5
250%	3.2	4.4	6.0	11.5

The external resistance applied by the elastic tubes (Table 3.5) was calculated based on Page *et al.*'s (2000) table of equivalent loads, using the average change in tube length (n=17) of T10 throughout the ROM of each exercise. Weight resistance remained constant throughout the ROM, while tubes exerted a lower resistance at the beginning of the ROM and a higher resistance at the end of the ROM and the combined condition was expected to offer an applied load that averaged that of the other two resistances on their own throughout the ROM.

Table 3.5 – Applied load (kg) relative to elbow joint positions throughout the full ROM of a bicep curl when training with tubes (T), weights (W) or a combination of the two (TW). Calculated based on measured average ROM when training with T10.

		LOAD AT START ROM (KG)	**LOAD AT 90° (KG)**	**LOAD AT END ROM (KG)**	**ROM (DEG)**
BICEP CURL	**T** (silver)	1.28	4.67	7.53	120°
	TW (blue + 2.8kg)	3.53	5.33	6.80	
	W (6kg)	6.00	6.00	6.00	
LATERAL RAISE	**T** (red)	0.41	-	2.80	180°
	W (1.8kg)	1.80	-	1.80	
LEG EXTENSION	**T** (silver)	1.28	-	12.40	130°
	TW (blue + 2.8kg)	3.53	-	9.25	
	W (6kg)	6.00	-	6.00	
LEG CURL	**T** (green)	0.49	-	2.63	55°
	W (2.3kg)	2.30	-	2.30	

Table 3.6 – Maximal tube strain recorded via 3d motion capture and equivalent loads, calculated from Page et al. (2000).

		T0	**T10**	**T20**	**W**
BICEP CURL	Tube strain	118% ± 14	141% ± 15	173% ± 17	
	Equivalent load	6.68kg	7.53kg	8.63kg	6.00kg
LATERAL RAISE	Tube strain	181% ± 13	212% ± 15	251% ± 16	
	Equivalent load	2.56kg	2.80kg	3.15kg	1.80kg
LEG EXTENTION	Tube strain	162%	191%	228%	
	Equivalent load	8.26kg	9.20kg	10.36kg	6.00kg
LEG CURL	Tube strain	100% ± 16	122% ± 17	150% ± 18	
	Equivalent load	2.30kg	2.63kg	3.02kg	2.30kg

When purchasing additional tubes for the final intervention study (Chapter 8), the manufacturer had changed the materials used in their products. After several exchanges with the manufacturer, it was decided to use two parallel strands of the new (2016) black tubing, which offered an equivalent load of 3.3Kg at 100% stretch, in order to keep resistances as similar as possible to the analytical studies. By combining two parallel strands of black tubing the total equivalent load at 100% stretch was 6.6Kg. Therefore, 6.6Kg dumbbells were used as a comparative load for the weight condition in Chapter 8 and one strand of black tubing with a dumbbell of 3.3Kg were used for the combined condition.

3.3.3.1.1 Tube lengths

Initial tube length was determined as follows. For the bicep curl (Figure 3.8-a) and the shoulder abduction (Figure 3.8-b), the distance between the end of the handle and the base of the foot was determined as tube length zero (T0); two more tube lengths were used by shortening T0 by 10% (T10) and 20% (T20). Tube length for the leg extension (Figure 3.8-c) was determined as the distance between the ankle of a seated person and the tube attachment at the back of the chair, which measured 50cm. The shortened tube lengths of 10% and 20% stretch for the leg extension resulted in 45cm and 40cm respectively. For practical purposes the tube was not tied to the chair during the studies, but anchored to the ground. For the standing leg curl (Figure 3.8-d), the initial tube length was determined as the distance between the velcro attachment at the ankle and the base of the standing foot, where the exercising knee was flexed at 135°; the other two tube lengths were determined by shortening the initial length by 10% and 20%. Once the initial tube lengths for the participant were determined, the measurements were marked with a permanent marker on the tube.

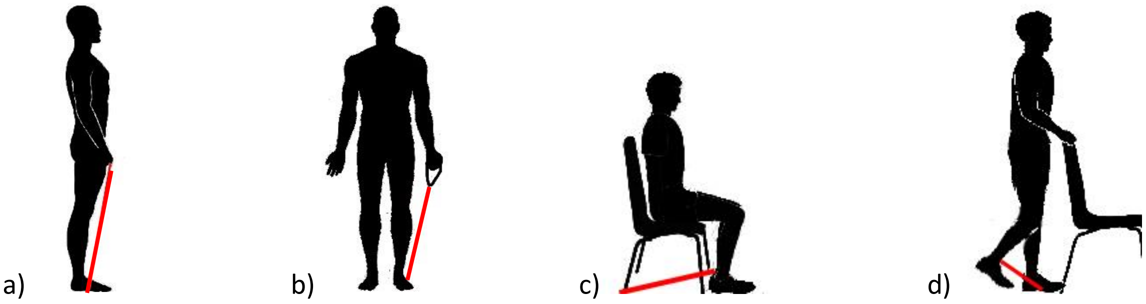


Figure 3.8 - Initial position and tube length for the bicep curl (a), the lateral raise (b), the leg extension (c) and leg curl (d).

3.3.3.1.2 Durability of elastic tubes

Given that elastic tubes are constructed in a degradable material, which is expected to alter its properties by extensive usage, it was considered important to ensure that the material properties of the equipment would not affect the results throughout the project. For this purpose, contact was established with Kingston University's Department of Engineering to test the durability of the elastic material through cyclic loading. Initial pilot testing was performed on a servo-hydraulic system, which did not prove sensitive enough to measure the tension offered by Thera-Band® tubing. A second contact was established with the Materials Laboratory, where the tubes were tested on a Zwick/Roell Tensile Tester (Ulm, Germany), which was not found appropriate for testing on supple materials. Finally, the tubes were tested on a Zwick/Roell Fatigue Tester (Ulm, Germany), which was sufficiently sensitive to test tensile strength of the tubes. Even though the Zwick/Roell Fatigue Tester (Ulm, Germany) was capable of testing over repeated cycles, the laboratory staff considered it unsafe to run cyclic tests in the 1,000s of repetitions as this could have overheated the equipment. Ultimately, despite many attempts to test the tubes for their reliability over time, it was not possible to do so with the equipment available. Fortunately, the literature offers sufficient information on the effects of cyclic loading on Thera-Band® tubing, where 5,000 stretch cycles of up to 200% elongation at various velocities did not significantly affect material properties of the tubes (Patterson *et al.*, 2001). Considering that the tubes were stretched less than 5,000 times throughout the project, it can be assumed that material properties were maintained equal in all studies.

3.3.3.2 Weight resistance

Free weights were used for the isotonic resistance throughout the study. A 6kg dumbbell was used for the bicep curl, a 1.8kg dumbbell was used for the lateral raise, a 6kg ankle weight was used for the leg extension and a 2.3kg ankle weight for the leg curl. Considering that an equal level of elastic resistance was assigned to all participants, the weight condition was calculated based on the equivalent load per elastic tube, as determined by the manufacturer (Table 3.4), and was thus equal for all participants.

3.3.4 Electromyography

3.3.4.1 Electrode Placement

A MyoMonitor IV, (DelSys Inc., Boston, USA) was used to record electromyography (EMG) data with Trigno wireless electrodes. Sampling rate was set at 1926Hz, which is considered an appropriate rate to accurately capture fundamental timing and amplitude measures of surface electromyography (Ives and Wigglesworth, 2003). In order to minimise skin impedance, which reduces data quality and increases noise, the skin was shaved, lightly abraded and thoroughly cleansed with alcohol wipes. Abrading removes dead skin cells in the selected area, while cleaning with alcohol removes impurities and skin oil (Blanc and Dimanico, 2009). The wireless electrodes were then attached to the skin with specifically designed hypoallergenic adhesive interfaces.

All electrodes were placed on the dominant limb only, following the guidelines of the “Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles” (SENIAM, 2012) for electrode placement unless otherwise stated. All electrodes were placed by the same researcher on all participants in order to minimise variation. Bony landmarks and muscle bellies were found through observation and palpation of anatomical sites; the placements mentioned hereafter have been used as guidelines and adjusted to the true, closest location of the muscle belly (SENIAM, 2012; De Luca *et al.*, 2012; Sawalha *et al.*, 2007).

- Electrode 1 was placed on the **Biceps Brachii** at one third the distance between the fossa cubita and the medial acromion, in direction towards the medial acromion. Given that EMG signals are stronger towards the lower portion of the muscle (Ahamed *et al.*, 2015), electrodes were positioned near the SENIAM (2012) location guideline on the centre of the muscle belly.
- Electrode 2 was placed on the lateral head of the **Triceps Brachii** at half the distance between the posterior crista of the acromion and the olecranon, following the diagonal orientation of the muscle fibres.

- Electrode 3 was placed on the **Trapezius Descendens** at half the distance between the acromion and the spine of the vertebra C7, in direction towards C7.
- Electrode 4 was placed on the **Deltoideus Medius** on the muscle belly in line between the acromion and the lateral epicondyle of the elbow, in direction towards the acromion.
- Electrode 5 was placed on the **Rectus Femoris** at approximately half the distance between the anterior superior iliac spine (ASIS) and the superior portion of the patella, following the ascending diagonal orientation of the muscle fibres. The muscle belly was found at the closest location next to the mentioned guidelines through palpation. Sensor placement for the Rectus Femoris muscle was validated by Sawalha *et al.* (2007) using ultrasonography, who reported that the appropriate mean electrode location should be 47% (range 33-60%) the distance between the anatomical landmarks.
- Electrode 6 was placed on the **Vastus Medialis** at 80% the distance between the ASIS and the joint space medial to the patella, in direction towards the ASIS.
- Electrode 7 was placed on the **Vastus Lateralis** at two thirds of the distance between the ASIS and the lateral side of the patella, in direction towards the ASIS.
- Electrode 8 was placed on the **Biceps Femoris** at half the distance between the ischial tuberosity and the lateral epicondyle of the tibia.
- Electrode 9 was placed on the **Gastrocnemius Lateralis** on the muscle belly, in direction towards the lateral epicondyle of the knee.

3.3.4.2 Maximal Voluntary Contraction

To normalise EMG data and express results as a percentage of maximal contraction, isometric maximal voluntary contractions (MVC) were recorded for all relevant muscles. Three MVCs of 3 seconds each were performed per muscle; the trial with the highest value was used for normalisation of the data obtained during the exercise trials.

- For the **biceps brachii** and **triceps brachii**, the dominant arm of the participant was fixed with an elbow flexion of 90° on a Biodex Dynamometer (Biodex Corporation, NY, USA); the participant was then asked to flex and extend their arm using their maximal force.
- For the **trapezius descendens** and the **deltoideus medius**, the participant's straight arm was fixed with a shoulder abduction of 90°. Participants were then asked to push upwards with their maximal strength.
- For the **rectus femoris**, the **vastus medialis**, the **vastus lateralis** and the **biceps femoris**, the participant's dominant leg was fixed to the dynamometer with a knee angle of 75° and a hip angle of 90°, and was asked to maximally extend and flex the leg respectively.

Participants were asked to push with their maximal force in all contractions and were allowed practice trials to become accustomed with the movement prior to commencing the test. While performing the test, participants were verbally encouraged to use their maximal strength in each contraction.

3.3.4.3 Limitations of Surface Electromyography

Surface EMG is a highly variable measurement and is subject to numerous factors which can directly or indirectly affect the signal. Factors include electrode placement and orientation with respect to muscle fibres, fibre type composition and size, blood flow, depth of fibre, adipose tissue thickness, cross talk from neighbouring muscles, noise of the electronic equipment, motion artefact and interference to name a few (Reaz *et al.*, 2006). Given this high variability, is it not unusual to find large standard deviations when collecting EMG data, despite normalising results to %MVC (De Luca, 1997), where trained and untrained individuals exhibit different levels of %MVC at equal force outputs (Fernandez Del Olmo *et al.*, 2006), and %MVC may also vary between trials of a same individual given that EMG is dependant hydration and fatigue (Reaz *et al.*, 2006), and MVC values are further affected by the participant's engagement during maximal tests. In the current study, this was corrected by recruiting participants of similar fitness levels, although individual differences would still have affected variation in data. Despite having taken all possible precautions to reduce the effects of these limitations, EMG data can still present substantial variance affecting statistical findings (Folland & Williams, 2007; De Luca, 1997). In light of these limitations, visible trends and near-statistical significances will be considered in the discussion as relevant findings where appropriate.

3.3.4.4 Reproducibility of EMG recordings

In order to assess the test-retest reliability of the EMG measurements, a total of 5 participants repeated some, or all, conditions in Study 1 on different days. Of the many available methods for testing statistical reliability, typical error of measurement was used for this project (Hopkins, 2015). The Pearson Correlation is reported to overestimate correlations for small sample sizes (Hopkins, 2000), it is insensitive to changes in mean and standard deviation (Sleivert and Wenger, 1994) and only measures linear associations, which is not appropriate for the nature of the activation patterns presented in this study (Larsson *et al.*, 2003). A widely used method for EMG is the Intraclass Correlation Coefficient (ICC) which, however, does not take into account the variance between measurements of a same individual (Bartko, 1966). Due to the high inter-subject variability that EMG presents, the *typical error of measurement*, which was adapted from the ICC and is also understood as the standard deviation of each subject's measurements between trials (Hopkins, 2000), was determined as the most appropriate method for this thesis. Typical error was calculated for every section of 20° of ROM using Hopkins' (2015) reliability spreadsheet and classified as per the author's instructions, where values of 0.2, 0.6, 1.2, 2.0 and 4.0 are interpreted as small, moderate, large, very large and extremely large respectively. The data portrays an overall moderate typical error, with 28% of values deemed small or very small, 55% moderate and 17% large. Agonist muscles showed greater reliability than antagonist and synergist muscles, which exhibited greater errors, especially in the weight condition. Given that secondary muscles vary in their level of engagement between individuals, it is not surprising that these would exhibit higher errors. The three muscles that portrayed the greatest errors were the triceps, the deltoid and the vastus medialis. The triceps is a relatively small muscle and, although it is easily located in individuals with high muscle mass, it is hard to locate in untrained subjects and its dimensions increase the chance of detecting cross talk. Readings for the deltoid medius, which also portrayed a high error, are prone to exhibiting a certain level of variation due the relative movement of the muscle fibres with respect to the electrode on the skin, as discussed in Section 2.5. Moreover, considering the electrode's proximity to the anterior and posterior portions of the deltoid muscle, which would have contributed to anteroposterior stabilization of the shoulder, an element of crosstalk may have also affected its signal. In the leg extension, the lower reliability of the vastus medialis and lateralis with respect to the rectus femoris is consistent with previous research and is speculatively caused by slight rotations of the thigh that occur during a leg extension which varies the load applied to either muscle (Kollmitzer *et al.*, 1999). It should also be noted that repeated tests were performed with an interval of several weeks, therefore it was not possible to control the location of the electrodes or the body composition of the participant between trials. Considering these, and other numerous factors that are inherent of the highly variable nature of EMG readings (Section 2.5.1), overall measures of typical error in this test demonstrate a highly acceptable level of repeatability.

As for joint angle specificity, data was heteroskedastic: error values appear to be spread out across all phases of movement and there is no apparent relationship between the reliability data and the sections of ROM.

It was not possible to calculate the typical error for the triceps brachii in the lateral raise, or for all muscles of the leg curl, due to only having repeated data from one participant.

Table 3.7 – Typical error values of the Leg Extension for each section of ROM in the elastic (T10) and weight (W) conditions.

MUSCLE	ROM	120°-100°	100°-80°	80°-60°	60°-40°	40°-20°	20°-0°	0°-20°	20°-40°	40°-60°	60°-80°	80°-100°	100°-120°
RECTUS FEM.	T10 (n=4)	1.05	0.51	0.37	0.44	0.52	0.65	1.01	0.87	0.63	0.52	0.64	0.46
	W (n=3)	1.00	1.00	0.75	1.10	0.35	0.91	0.59	1.08	1.03	0.98	0.80	1.00
VASTUS MED.	T10 (n=3)	1.11	0.51	0.61	0.48	0.56	0.54	0.21	0.88	1.25	1.40	1.24	1.18
	W (n=2)	1.14	1.10	0.32	0.07	0.60	0.86	1.25	1.38	1.34	1.41	1.34	1.00
VASTUS LAT.	T10 (n=4)	0.91	0.92	0.97	0.93	0.93	1.24	1.15	0.97	0.98	0.97	0.92	0.92
	W (n=3)	1.02	0.98	0.92	0.85	0.88	0.97	0.94	0.99	1.01	1.03	1.03	1.02
BICEPS FEM.	T10 (n=3)	1.20	1.18	1.16	1.06	1.03	0.90	1.00	1.12	1.18	1.18	1.18	1.08
	W (n=2)	0.59	0.73	0.96	0.82	0.73	0.06	0.45	0.78	1.00	1.34	1.00	1.26

Table 3.8 – Typical error values of the Bicep Curl for each section of ROM in the elastic (T10) and weight (W) conditions.

MUSCLE	ROM	160°-140°	140°-120°	120°-100°	100°-80°	80°-60°	60°-40°	40°-20°	20°-40°	40°-60°	60°-80°	80°-100°	100°-120°	120°-140°	140°-160°
BICEPS	T10 (n=5)	0.37	0.24	0.39	0.24	0.71	0.24	0.18	0.48	0.79	0.14	0.22	0.27	0.65	0.92
	W (n=3)	0.42	0.08	0.03	0.15	0.19	0.24	1.10	1.24	1.04	0.76	0.05	0.10	0.25	0.22
TRICEPS	T10 (n=4)	0.97	0.99	0.97	0.95	1.22	1.22	1.26	1.25	0.99	1.17	1.17	1.06	1.05	0.54
	W (n=3)	1.04	1.04	1.06	1.06	1.21	1.16	0.28	1.39	1.29	1.24	1.30	1.29	1.16	1.35

Table 3.9 – Typical error values of the Lateral Raise for each section of ROM in the elastic (T10) and weight (W) conditions.

MUSCLE	ROM	170°-150°	150°-130°	130°-110°	110°-90°	90°-70°	70°-50°	50°-30°	30°-50°	50°-70°	70°-90°	90°-110°	110°-130°	130°-150°	150°-170°
BICEPS	T10 (n=2)	0.72	0.79	0.89	0.88	0.93	1.00	1.04	1.03	0.97	0.95	0.92	0.89	0.90	0.94
	W (n=2)	1.18	0.73	0.28	1.15	1.41	0.87	0.22	0.45	0.45	0.59	0.20	0.00	0.28	0.00
DELTOID	T10 (n=2)	1.39	1.08	0.76	1.03	1.38	1.32	0.01	1.26	1.37	1.40	1.86	0.23	0.63	0.36
	W (n=2)	1.22	1.41	1.40	1.26	1.22	0.96	0.83	1.34	1.21	0.83	0.69	0.95	0.00	0.84
TRAPEZ.	T10 (n=2)	1.41	1.38	1.26	0.83	0.69	0.16	0.27	0.75	0.73	0.57	0.19	0.20	1.30	1.26
	W (n=2)	0.98	0.94	0.98	0.78	0.83	0.69	0.62	0.35	1.07	0.71	0.56	0.51	1.30	0.16

3.3.5 3D Motion Analysis

3.3.5.1 System setup

Qualisys Track Manager (Qualisys Medical AB, Savedalen, Sweden), was used to capture 3D motion during all exercises of all four analytical studies, using a total of six Oquus cameras. Motion capture frequency was set at 231Hz frame rate in order to accurately capture joint movements at movement velocities reaching 180deg·$^{-1}$ (Payton and Barlett, 2007), unless otherwise stated.

3.3.5.2 Marker placement

Retro-reflective markers for motion capture were placed on bony landmarks, found through palpation and observation, with hypoallergenic adhesive tape. For the exercising limbs, markers were placed on the acromion (A), the lateral epicondyle of the elbow (B), the styloid process of the radius (C), the greater trochanter (D), the lateral epicondyle of the knee (E) and the lateral malleolus of the ankle (F) (Figure 3.9).

The movements of the elbow joint during the bicep curl were measured in the sagittal plane by analysing the angle between the markers A, B and C. The movements of the shoulder during the lateral raise were measured in the frontal plane as the angle between markers B, A and the vertical axis. The movements of the leg during the leg extension and the leg curl were measure in the sagittal plane as the angle between markers D, E and F.

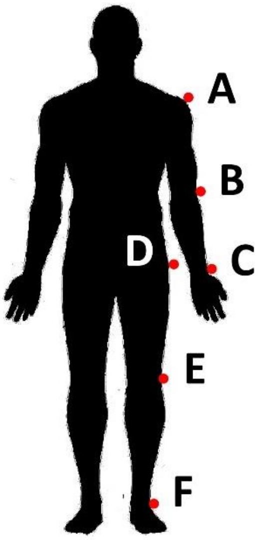


Figure 3.9 – Placement of retroreflective markers throughout all analytical studies.

3.4 Data processing and analysis

3.4.1 Data analysis

Muscular activation data was recorded through Trigno wireless electrodes at 1926Hz, while motion capture data was recorded using Oquus infrared cameras and retroreflective markers at 231Hz. The two systems were integrated by using a Delsys Trigno Trigger Module, which enables the actioning of both the EMG and 3D capture at the same time, enabling the researcher to have two synchronised data sets with matching starting points. Both data sets were recorded through Qualysis Track Manager.

Data was copied as text only from Qualysis, transferred to an Excel spreadsheet, saved as a comma delimited files (.csv) and then imported into EMGworks Analysis. Frame rate was specified per each file when imported as 1926 for EMG data and 231 for 3D data. The EMG data per muscle, per exercise, was processed through root mean square (RMS), then normalised to %MVC and plotted as subplots alongside the joint angles (3D data) for each trial (Figure 3.10). A band-pass filter of 20-450 Hz was automatically applied to the EMG data by the sensors, which reduced motion artefact and baseline noise contamination (De Luca *et al.*, 2011, 2010).

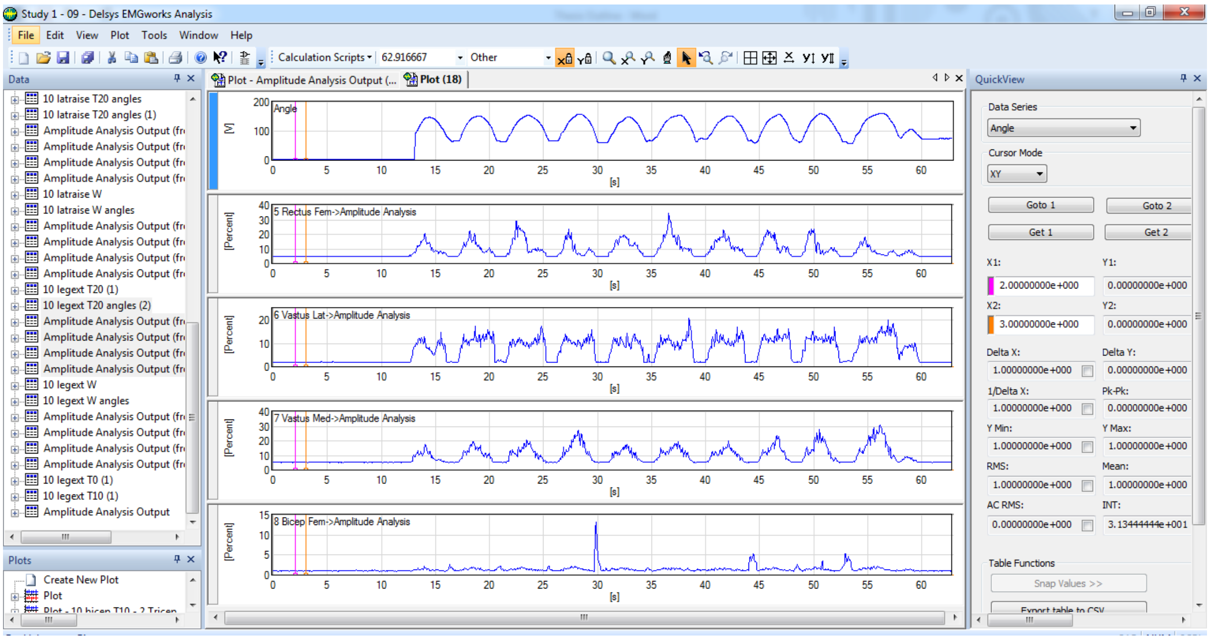


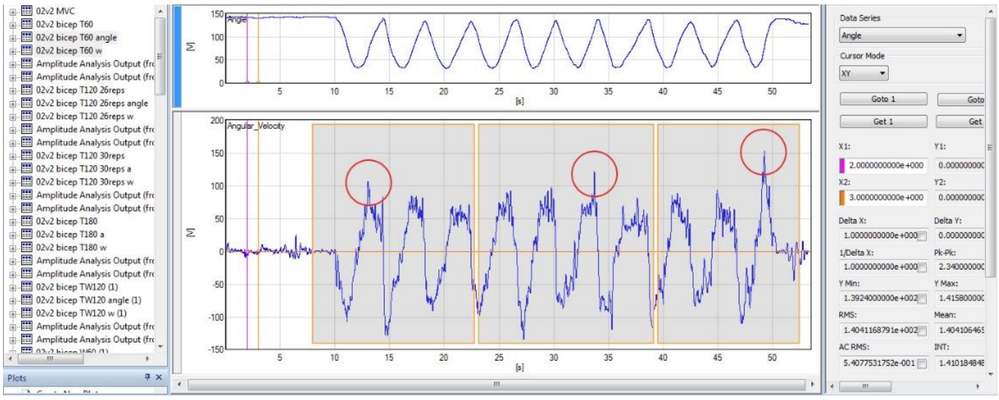
Figure 3.10 – EMGworks Analysis interface after having plotted muscle activation (%MVC) and joint angles (deg) of a leg extension.

3.4.2 Muscular activation patterns

Once joint angles and muscular activation were plotted as synchronised data in EMGworks, the average muscular activation per every 20° of joint angle interval was recorded and averaged over three repetitions. Movements were divided into 20° segments in order to provide a trendline that was sufficiently accurate for reflecting oscillations in muscular activation throughout the ROM. Reducing the analysis windows to short epochs of the contraction (20° ROM) and averaging values over three repetitions from the same set, should have minimised the variability in EMG readings which, as discussed in Section 2.5, are susceptible to changes due to the movement of the muscle fibres with respect to the electrode during dynamic contractions.

3.4.3 Peak and total muscular activation

Peak activation was determined as the mean of three peaks within a set of ten repetitions: the highest peak from the first three repetitions, the highest peak from the middle four repetitions and the highest peak from the last three repetitions (Figure 3.11). Total activation was determined as the integration of the EMG curve of the full set of ten repetitions, EMG integration is a commonly used method to evaluate muscular activation over time and offers high reliability for measurements during dynamic exercise (Sleivert and Wenger, 1994). To represent the data, total activation for the elastic conditions was then normalised to the weight condition by reporting the former as a percentage of the latter. Both peak and integration calculations were made after having filtered and normalised the EMG signal through RMS and %MVC.



Data Series: Angle
Cursor Mode: XY
X1: 2.0000000000e+000
Y1: 0.000000000
X2: 3.0000000000e+000
Y2: 0.000000000
Delta X: 1.0000000000e+000
Delta Y: 0.000000000
1/Delta X: 1.0000000000e+000
Pk-Pk: 2.340000000
Y Min: 1.3924000000e+002
Y Max: 1.415800000
RMS: 1.4041168791e+002
Mean: 1.40410646
AC RMS: 5.4077531752e-001
INT: 1.41018484

Figure 3.11 – EMGworks Analysis interface and example of selection of peak values for data analysis.

3.5 Statistical analysis

All statistical analyses were performed using the statistics software IBM SPSS 24 (IMB SPSS Inc, Chicago, USA). Normality was assessed through visual exploration of the data and a Shapiro-Wilk test given its recommended use in samples smaller than 30 (Ghasemi & Zahediasl, 2012). Type I error was addressed by setting alpha at 0.05 for the ANOVAs. Type II error was addressed by taking into account effect size (using ETA squared) and observed power, which were computed using the SPSS 24 software. Some of the studies presented in this project comprised of a small sample size (eg. Chapter 8), in which case visible trends were taken into consideration in the discussion of the results.

For total and peak activation, a two-way within subjects repeated measures ANOVA was performed to determine whether differences in muscle activation existed between conditions (alpha=0.05). LSD post-hoc was used to locate significant differences (alpha=0.05). For muscular activation patterns, a separate ANOVA (alpha=0.05) was performed for the concentric and eccentric phases with two factors: Resistance (2-4 levels depending on the study) and ROM (7 levels for the bicep curl, 8 levels for the lateral raise, 6 levels for the leg extension and 4 levels for the leg curl).

In studies where the patterns of only two resistances were compared (i.e. Studies 2, 5), *post-hoc* pairwise comparisons were performed with Bonferroni correction to locate differences at specific points in the ROM. In studies where more than two resistances were compared (i.e. Studies 1, 3), a second ANOVA with one factor (Resistance) was performed as *post-hoc* for each section of ROM, LSD *post-hoc* was then used to locate significant differences (alpha=0.05)

Chapter 4

Muscular activation patterns under elastic and weight resistances

4.1 Abstract

🕮 Aspects of this chapter were presented at the "21st Annual Congress of the European College of Sport Science" July 6-9th 2016 (Vienna, Austria), and published in the book of abstracts.

INTRODUCTION: Elastic resistance training has become commonly used in both strength and muscular rehabilitation settings. Scientific research has so far analysed differences in load and muscular activation between elastic resistance and isotonic methods of resistance, although most publications have addressed levels of muscular activation in terms of mean, peak or total activation, without fully considering differences in activation at specific joint angles. The aim of the current study was to analyse patterns of muscular activation elicited by elastic versus free weight resistance in four common exercise modalities across the range of motion.

METHODS: Seventeen moderately active males (age= 26 ± 8) performed a set of 10 repetitions per condition for four exercises: bicep curls, lateral raises, leg extensions and standing leg curls, all executed at $60\text{deg}\cdot\text{s}^{-1}$. Each exercise was performed under four conditions: with three different initial lengths of elastic tubing: T0 (0% stretch), T10 and T20 (10% and 20% reduction in initial tube length respectively) and one free weight of equivalent resistance to the tube (W) as determined by the tube manufacturer. Surface electromyography (EMG) was recorded for the biceps brachii (BB), tricep brachii (TB), deltoid medialis (DM), trapezius descendens (TD), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), bicep femoris (BF) and gastrocnemius lateralis (GL) using wireless electrodes (1926Hz) and was normalised to maximal voluntary contraction (MVC); joint movements were recorded through 3D motion capture (60Hz). Peak muscular activation and average activation per every 20° of range of motion (ROM) were averaged from three repetitions of each muscle, per condition, per exercise; total activation was calculated as the integrated EMG curve over a full set of ten repetitions. Data for each variable was analysed by within subject repeated measures ANOVA with LSD *post-hoc*.

RESULTS: T0 elicited lower ($p<.05$) activation than T20 at varying stages of the bicep curl (BB, TB), lateral raise (DM, TD, BB) and leg extension (RF, VM, VL, BF).

Total activation was higher ($p<.05$) in the elastic condition for the lateral raise (DM, TD, BB) and leg extension (VL, VM); while in the leg curl (GL), leg extension (RF, BF) and bicep curl (BB) weights elicited higher ($p<.05$) total activation.

Peak activation was higher ($p<.05$) in the elastic condition for the DM in the bicep curl and the BB in the lateral raise; the BB showed similar peaks under both resistances for the bicep curl. RF and BF peak activation was higher ($p<.05$) in the weight condition during in the leg extension.

Elastic resistance elicited lower ($p<.05$) muscular activation than weight resistance at the beginning of the ROM of the bicep curl (BB), leg curl (BF, GL) and leg extension (BF); and higher ($p<.05$) activation at the end of the ROM of the bicep curl (BB, TB, DM), lateral raise (DM, TD, BB) and leg extension (VL). All other muscles followed similar trends in all conditions, though not reaching statistical significance.

DISCUSSION: Elastic resistance elicited lower muscular activation than weight resistance at initial stages of movement, and higher activation at final stages of movement, where weight resistance generally showed a drop in muscular activation. Auxiliary muscles were generally more active under elastic resistance, suggesting that this method may be more appropriate than weights for proprioceptive training. Antagonist muscle responses varied between exercises. In conclusion, given the material properties of elastic tubing, elastic training provoked opposing muscular activation patterns to weight training, where as one increased the other decreased, indicating that the two training methods may elicit muscular adaptations at differing muscle lengths, and may be effectively used as complementary training methods.

4.2 Introduction

Elastic materials are known to produce tension that increases with their elongation (Santos *et al.*, 2009). Exercising with elastic resistance is therefore expected to produce greater muscular activation at the end of the range of motion (ROM) in response to its increasing external resistance (Frost *et al.*, 2010). However, most research into the effect of elastic training has addressed muscular activation in terms of total, mean or peak EMG, while specific patterns of muscular activation throughout the full range of movement have been scarcely considered (Jakobsen *et al.*, 2014, 2013; Aboodarda *et al.*, 2013).

There are conflicting findings regarding overall muscular activation with elastic resistance training compared to isotonic methods of resistance (i.e. weights, pulley machines, dynamometers). Research suggests that elastic resistance can elicit magnitudes of peak EMG of the agonist muscle similar to those elicited with weight resistance (Jakobsen *et al.*, 2014, 2013; Serner *et al.*, 2014; Aboodarda *et al.*, 2013; Matheson *et al.*, 2001), with the possibilities of reaching high loads (~90%MVC) (Aboodarda *et al.*, 2012); although some studies reported a higher activation of the agonist muscle under elastic resistance (Sundstrup *et al.*, 2014; Brandt *et al.*, 2013; Sundstrup *et al.*, 2012). In addition, there is some evidence to suggest a greater activation of the antagonist muscle during proprioceptive exercises and lunges (Sundstrup *et al.,* 2014; Schulties *et al.*, 1998), although most studies with similar methodologies to those implemented here did not measure muscular activation of antagonist muscles, giving little opportunity for comparison (Aboodarda *et al.*, 2013, 2011; Andersen *et al.*, 2010; Matheson *et al.*, 2001). The variable resistance offered by elastic materials renders it difficult to standardise testing procedures and may have contributed to the difference in responses reported by the mentioned studies, stressing the need for more detailed explorations of muscle activation during elastic resistance exercise.

Furthermore, the literature does not demonstrate a consensus on whether there is a clear effect of elastic training on auxiliary muscle recruitment in comparison to isotonic exercise. Several studies reported a significantly higher activation of stabilizer muscles with elastic resistance (Vinstrup *et al.*, 2015; Sundstrup *et al.*, 2014; Jakobsen *et al.*, 2014; Lister *et al.*, 2007), although several others found no difference to weight resistance (Serner *et al.*, 2014; Brandt *et al.*, 2013; Sundstrup *et al.*, 2012; Witt *et al.*, 2011; Matheson *et al.*, 2001). It is worth noting that some of the aforementioned studies reported using different exercise set-ups between the elastic and isotonic conditions, which would have affected muscle activation and recruitment due to differing directions of applied forces (Sundstrup *et al.*, 2014; Simoneau *et al.,* 2001).

Although these findings give a general perspective on how elastic and isotonic resistance differ in terms of overall muscle engagement, portraying EMG data as mean and peak values does not facilitate the investigation of specific muscular activation patterns throughout the ROM. Early publications suggested a near-isotonic behaviour of elastic loads due to the interaction of variable loads with mechanical advantage throughout the ROM (Page, 2002; Hughes *et al.*, 1999), although it has been more recently observed that, because resistive force increases with the elongation of the elastic tube (McMaster *et al.*, 2010) with stiffer tubes presenting a steeper stress-elongation curve (Santos *et al.*, 2009), this normally results in an increment of applied force towards the final phases of movement (Jakobsen *et al.*, 2014). In fact, elastic resistance appears to recruit different magnitudes of muscle activation in different phases of movement compared to weight resistance (Jakobsen *et al.*, 2014; 2013), specifically eliciting a greater activation towards the final phases of the ROM with respect to isotonic resistance (Jakobsen *et al.*, 2014; Aboodarda *et al.*, 2013). Research also indicates that, contrary to most weight-resisted exercises, elastic resistance places load over a greater portion of the ROM (Wallace *et al.*, 2006; Ebben and Jensen, 2002) where the initial length of an elastic tube influences the degree and duration of muscle activation throughout the ROM of an exercise (Aboodarda *et al.*, 2011). Having further established that a 10% to 30% reduction in the initial length of the elastic tubes significantly increases mean and peak EMG (Aboodarda *et al.*, 2013; Andersen *et al.*, 2010; Hodges *et al.*, 2006; Matheson *et al.*, 2001), the effects of shortening initial tube lengths on specific patterns of muscular activation should also be considered in order to identify whether initial tube length causes any significant changes in the activation curve. It is common practice to reduce the initial length of the tube in order to place greater loads at initial phases of movement, however a significant change in tension may also affect the occurrence of peak activation and the ROM of execution, which would ultimately influence any muscular adaptations and performance outcomes.

Despite the differing shapes in the activation curves elicited by elastic and weight resistances, Aboodarda *et al.* (2016) argued that, when the limb moves throughout the entire ROM, and the average EMG denotes a similar overall muscular activation in both conditions, equivalent strength gains should be observed (Hakkinen, 1989). However, focusing long term strength training at different muscle lengths is known to effect a change in the number of in-series sarcomeres per fibre (Brughellli *et al.*, 2010; Rassier *et al.*, 1999), affecting the muscle's strength at different stages of contraction and consequently making it more, or less, prone to injury (Timmins *et al.*, 2016). Therefore, given the plasticity of muscle fibre architecture, understanding the length specificity of muscular activation patterns generated by a variable resistance would help determine its applicability for different resistance training programmes.

Having considered that elastic and weight resistance exert muscles at differing stages of ROM, and that these differences may have important implications for muscular strength and architectural adaptations, this study aims to analyse muscular activation patterns during elastic resistance exercise and to understand how they differ from weight resistance exercise.

4.3 Methodology

4.3.1 Participants

Seventeen moderately active males (age= 26 ± 8 years; stature= 176 ± 7 cm; mass= 77 ± 14 kg) were recruited for the study on a voluntary basis. All participants signed an informed consent and PAR-Q form before testing (Appendix A). The study was approved by Kingston University Faculty's Ethic committee in line with the declaration of Helsinki.

4.3.2 Resistances

Thera-Band® elastic tubing was individually prepared (Section 3.3.3) at three different initial lengths per participant (T0, T10 and T20), while a dumbbell or ankle weight was used for the weight condition (W). Initial tube length (T0) was determined as the distance between the handle and the floor anchor point, while T10 and T20 were measured as a decrease of 10% and 20% in length respectively from T0. As per manufacturer's recommendations of equivalent loads taken from Page *et al.* (2000), bicep curls were performed with 6kg dumbbells or silver tubing, lateral raises with 1.8kg or red tubing, leg extensions were performed with 6kg ankle weights or silver tubing and leg curls with 2.3kg or green tubing.

The external resistance applied by the elastic tubes (Table 3.3) was calculated based on Page *et al.*'s (2000) table of equivalent loads, using the average change in tube length (n=17) of T10 throughout the ROM of each exercise.

4.3.3 Procedures

The study consisted of recording muscular activation throughout the ROM of four exercises: bicep curls, lateral raises, leg extensions and standing leg curls, each tested under four conditions (T0, T10, T20, W). Before the tests, the participant's skin was thoroughly cleaned and Trigno surface wireless electrodes (DelSys Inc., Boston, USA) were positioned on each muscle in accordance with SENIAM guidance (SENIAM, 2012) (Section 3.4.1). Retroreflective markers were then placed on bony landmarks of exercising limbs for use during 3D motion capture in order to record joint angles (Section 3.4.2).

Participants warmed up with dynamic exercise for 5 minutes, which included jogging and dynamic stretches of the arms and legs. Participants then performed unilateral isometric maximal voluntary contractions (MVC) on a Biodex Dynamometer (Biodex Corporation, NY, USA) for all tested muscles (Section 3.4.1). In a random order, participants then performed a set of ten unilateral repetitions with the dominant limb for each condition at an average angular velocity of 60deg$\cdot$s^{-1}. Three minutes of resting time were allowed between sets to avoid fatigue. Movement velocity was controlled with a video of every exercise performed at constant velocity; the participants were required to practice mirroring the video without resistance before the trials to become accustomed to the velocity, the video was then left running throughout testing as a reference for movement velocity.

4.3.4 Data sampling and processing

EMG (mV) was recorded for the biceps brachii, triceps brachii, trapezius descendens, deltoid medialis, rectus femoris, vastus lateralis, vastus medialis, biceps femoris and gastrocnemius lateralis with Trigno wireless electrodes at 1926Hz (refer to Section 3.4.1 for detailed procedures and set up). Participants performed three MVCs for each muscle prior to commencing the trials, which were then used to calculate EMG data as a percentage of their maximal contraction (%MVC) in order to normalise between participants. Raw EMG data was averaged by root mean square (RMS) and plotted as activation (%MVC) against joint angle (degrees) through EMGworks Analysis software. Peak EMG was recorded as the mean of three peaks, each taken from the first three repetitions, the middle four, and the final three respectively. Total activation was calculated as the integrated RMS EMG curve over a full set of ten repetitions, where total activation for the elastic conditions was normalised to the weight condition by reporting the former as a ratio of the latter. Muscular activation patterns were drawn by calculating the average EMG for every 20° of ROM from three repetitions of each set. Joint angles (Section 3.3.5) were tracked using 3D motion capture through Qualysis Track Manager at 60 Hz.

4.3.5 Biomechanical calculations

Alongside recording actual muscular activation throughout the ROM, the theoretical resistive force required by the biceps brachii to overcome resistance throughout the bicep curl was calculated. Calculations were first made for the theoretical external resistance applied by the tubes (silver, T10) and the dumbbells (6kg), assuming the humerus remained vertical throughout the ROM, using the following formula:

$$F_R = R \times d_R$$

where F_R is the torque applied by the external resistance (Nm), R is the magnitude of the external resistance (N), calculated according to % stretch per each elbow angle for the elastic condition, and d_R is the moment arm of the applied external resistance (m), calculated as the measured mean distance from the lateral epicondyle of the humerus to the centre of the palm. Subsequently, the theoretical resistive force required by the biceps to counteract the external resistance was calculated as follows:

$$\mathrm{F_{BB}} = \frac{\mathrm{F_R} * \mathrm{d_R}}{\mathrm{d_{BB}}}$$

where F_{BB} is the resultant force required by the biceps brachii to counteract F_R (Nm) and d_{BB} is the moment arm of the biceps action on the humerus (m) determined from the anatomical studies of Murray *et al.* (1995) and Pigeon *et al.* (1996) as 0.03m, 0.041m and 0.02m for 150°, 90° and 30° elbow angle respectively.

4.3.6 Statistical Analysis

A Shapiro-Wilk test was used to determine normality using the statistics software IBM SPSS 24 (IMB SPSS Inc, Chicago, USA). Effect size (ETA squared) and observed power were also computed using the software. A two-way within subjects repeated measures ANOVA was performed for the mean, peak and total activation of each exercise, to determine whether differences in muscle activation existed between the various tube lengths and the weight condition. The repeated measures ANOVA of the activation patterns was performed separately for the concentric and eccentric phases and had two factors, Resistance (four levels: T0, T10, T20 and W), and ROM (7 levels for the bicep curl, 8 levels for the lateral raise, 6 levels for the leg extension and 4 levels for the leg curl). Critical *P* value was set at 0.05 for all tests. LSD post-hoc was used to locate significant differences.

4.4 Results

4.4.1 Bicep curl

4.4.1.1 Biceps Brachii

Total muscular activation of the biceps brachii (Figure 4.1) was higher (p≤.015) for W than for T0 and T10, and significantly increased (p<.001) with reduced tube lengths for elastic conditions. Biceps activation peaked at different elbow angles under the two resistances, occurring at the end of the ROM (30° elbow angle ±10°) in all elastic conditions and at mid ROM (80°±10°) for the weight condition (Figure 4.3), and was not significantly different between resistance methods (Figure 4.2). Peak muscular activation did however increase significantly (p=.016) with shorter tubes within the elastic conditions (Figure 4.2). All elastic conditions elicited a significantly lower activation than weight resistance at early stages of the ROM and higher activation at the end of ROM in the concentric phase (p<0.001), while differences are visible but not statistically significant (p=.06) in the eccentric phase (Figure 4.3).

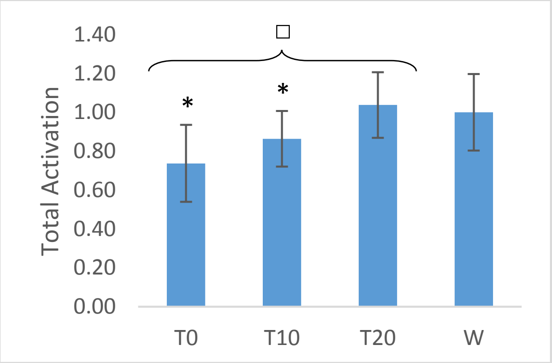


*Figure 4.1 - Ratio of total muscular activation (n=15) of the Biceps Brachii when performing a Bicep Curl under four different conditions (T0,T10,T20,W). * Significant difference (p≤.015) between W and T0,T10; □ Significant difference (p≤.002) between all elastic conditions*

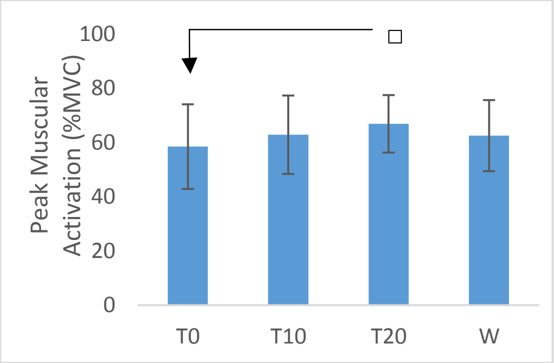


Figure 4.2 - Mean ± SD (n=15) peak muscular activation of the Biceps Brachii when performing a Bicep Curl under four different conditions (T0,T10,T20,W). □ Significant difference (p=.016) between T0 and T20.

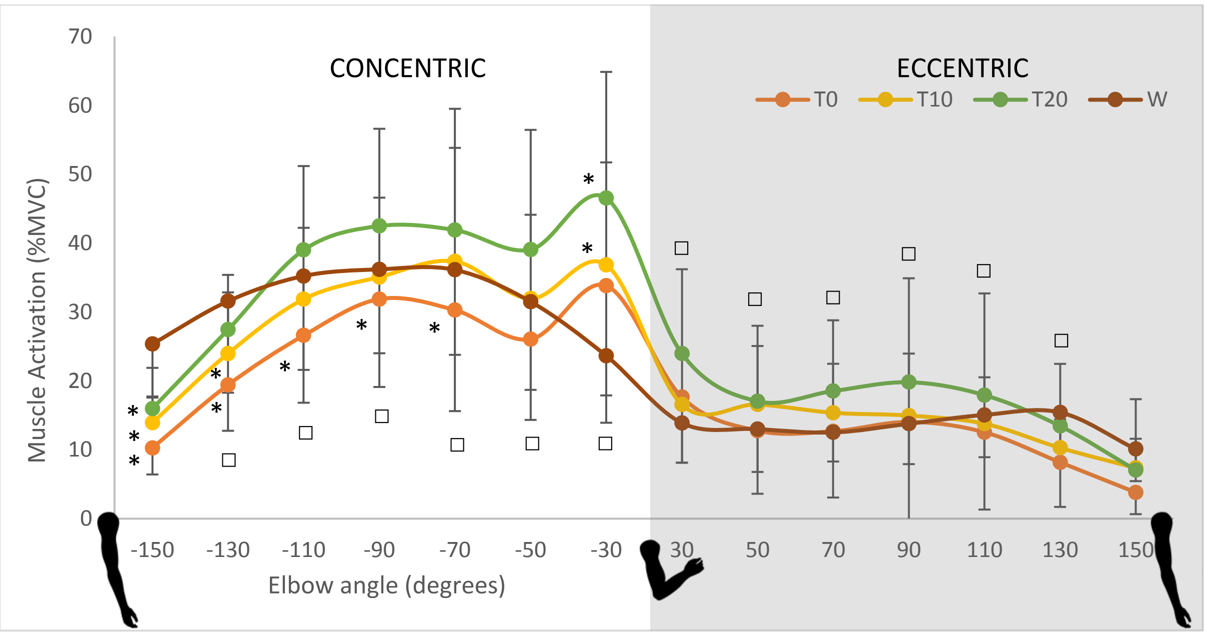


*Figure 4.3 - Mean ± SD muscular activation (n=17) of the Biceps Brachii per every 20° of ROM, throughout the entire range of motion of a Bicep Curl, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition; □ Significant difference (p<0.5) among tube conditions.*

4.4.1.2 Triceps Brachii

During the bicep curl, total triceps activation showed an increasing trend with shorter tubes under elastic resistance, which was not significantly different from the weight condition (Figure 4.4). Peak activation (Figure 4.5) tended to be higher (p=.08) in all elastic conditions compared to W, although the data was not sufficiently powerful (observed power = 0.45) to reach statistical significance. In the concentric phase, all conditions elicited similar activation of the triceps throughout most of the ROM except at 30 ± 10° elbow angle (Figure 4.6), where activation peaked under all elastic conditions and dropped under W, though not reaching statistical significance (p=.08). Although trends are clearly visible in all three representations of triceps activation, high variance in the data was responsible for the lack (p=.08) in statistical significance.

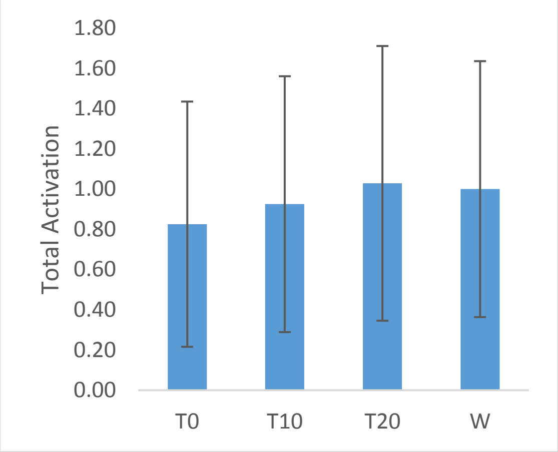


Figure 4.4 - Ratio of total muscular activation (n=15) of the Triceps when performing a Bicep Curl under four different conditions (T0,T10,T20,W).

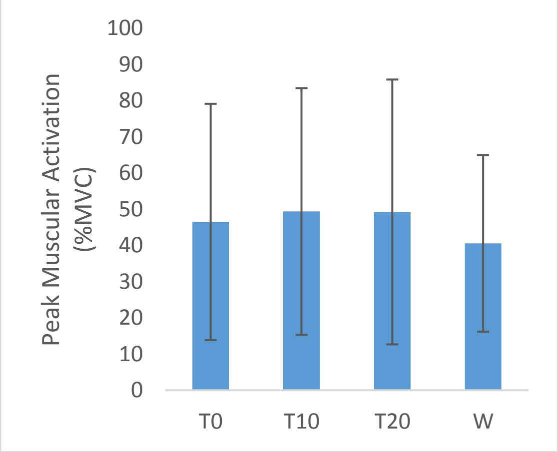


Figure 4.5 - Mean ± SD (n=15) peak muscular activation of the Triceps when performing a Bicep Curl under four different conditions (T0,T10,T20,W).

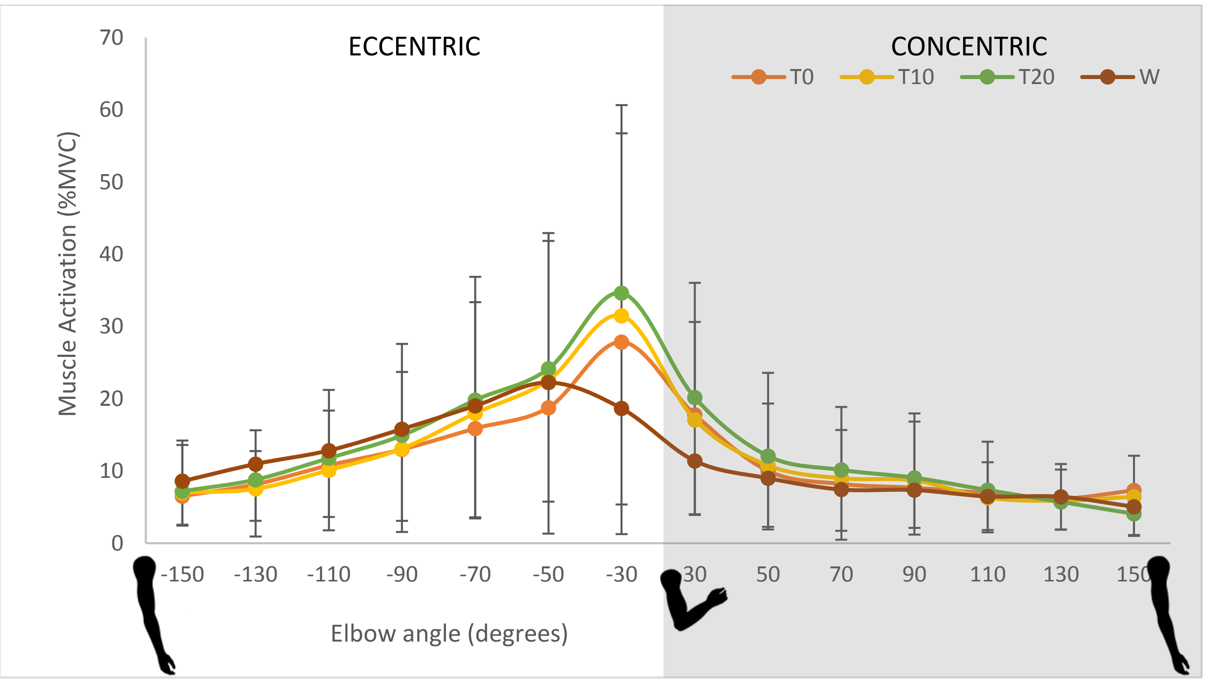


Figure 4.6 - Mean ± SD muscular activation (n=17) of the Triceps Brachii per every 20° of ROM, throughout the entire range of motion of a Bicep Curl, under four different conditions (T0,T10,T20,W).

4.4.1.3 Deltoid Medius

During the bicep curl, total activation of the deltoid medius was significantly higher (p=.05) under T20 than in the weight condition (Figure 4.11Figure 4.7). Deltoid peak activation was significantly higher (p=.001) under T10 and T20 with respect to W (Figure 4.8). Patterns in muscular activation (Figure 4.9) revealed a noticeable difference in the concentric phase (p=.009) between resistances throughout the ROM, where all elastic conditions exhibited large peaks at the end of the ROM (70-30° elbow angle) and the weight condition exhibited a peak at the beginning of the ROM (130°).

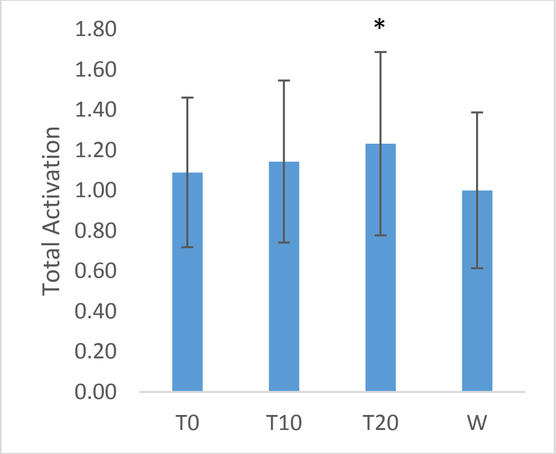


*Figure 4.7 - Ratio of total muscular activation (n=10) of the Deltoid Medius when performing a Bicep Curl under four different conditions (T0,T10,T20,W). *Significant difference (p=.05) from W.*

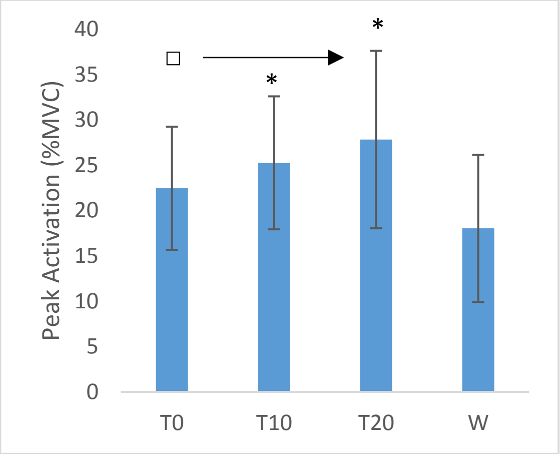


*Figure 4.8 - Mean ± SD (n=10) peak muscular activation of the Deltoid Medius when performing a Bicep Curl under four different conditions (T0,T10,T20,W). *Significant difference (p=0.001) from W. □ Significant difference between T0 and T20 (p=.017).*

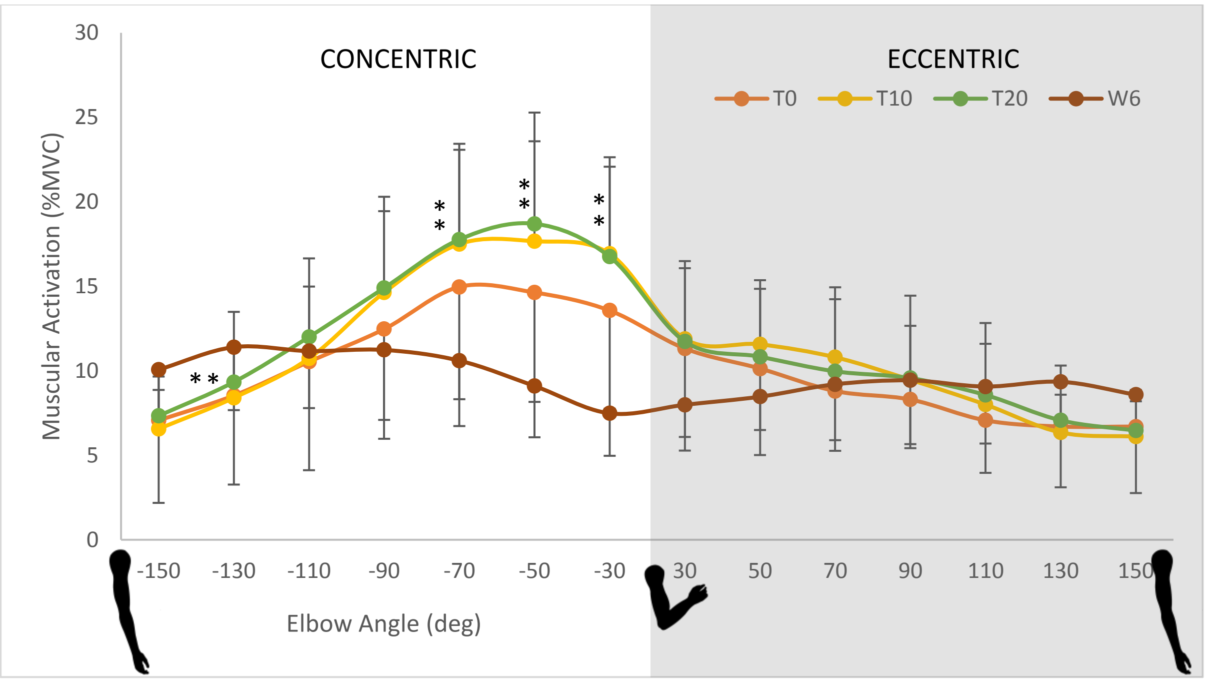


*Figure 4.9 - Mean ± SD muscular activation (n=17) of the Deltoid Medius per every 20° of ROM, throughout the entire range of motion of a Bicep Curl, under four different conditions (T0,T10,T20,W). * Significant difference from weight condition (p≤.007).*

4.4.1.4 Biomechanical Analysis

The range of shoulder flexion was significantly higher ($p<.05$) in the elastic condition, where the elbow also exhibited greater mediolateral movement, though not reaching statistical significance (Table 4.1).

Table 4.1 – Range of shoulder and elbow movements throughout the bicep curl. NOTE: The forearm inclination value for T10 is an estimate, calculated from 3D data recorded from Qualisys.
**Significant difference between range of shoulder extension of tubes and weights.*

	WEIGHTS	TUBES (T10)
Range of shoulder flexion	23° ± 8	33° ± 10*
Range of horizontal shoulder ad/abduction	6° ± 3	9° ± 5
Forearm inclination (relative to the direction of force application at end ROM)	9° ± 15	25°

The increases in theoretical resistive force required by the biceps did not match the incremental patterns of the actual experimental muscular activation. More specifically, at 30° elbow angle where resistive force was expected to plateau with the weights, muscular activation decreased, and it increased more than expected with the tubes (Table 4.2).

*Table 4.2 - Theoretical resultant force (silver tubes, 6kg weights) and experimental muscular activation (T10, W) of the biceps brachii during the bicep curl. * Significant difference between tubes and weights.*

	WEIGHTS	TUBES (T10)
Biceps mean activation at 150° elbow flexion (%MVC)	25 ± 28	14 ± 15*
Resistive force required by biceps at 150° elbow flexion (N)	294	78*
Biceps mean activation at 90° elbow flexion (%MVC)	36 ± 34	35 ± 36
Resistive force required by biceps at 90° elbow flexion (N)	441	326
Biceps mean activation at 30° elbow flexion (%MVC)	24 ± 19	37 ± 27*
Resistive force required by biceps at 30° elbow flexion (N)	441	466

Table 4.3 – Mean elbow angle where the load of the tubes was equivalent to the load of the dumbbell (6kg)

	T0	T10	T20
Elbow angle	45° ± 11	62° ± 9	79° ± 8

4.4.2 Lateral Raise

4.4.2.1 Deltoid Medius

During the lateral raise, all elastic conditions elicited higher total activation of the deltoid (Figure 4.10), although only reaching significance (p=.05) for T10 and T20. Peak activation showed a tendency of being higher under all elastic conditions with respect to W (Figure 4.11), although it did not reach statistical significance. Muscular activation patterns of the deltoid medius (Figure 4.12) showed a similar trend for all the conditions throughout the entire eccentric phase and most of the concentric phase, except for final stages of ROM (120° to 180° shoulder angle) where activation dropped significantly (p=.032) with weight resistance and increased under elastic resistance (Figure 4.12).

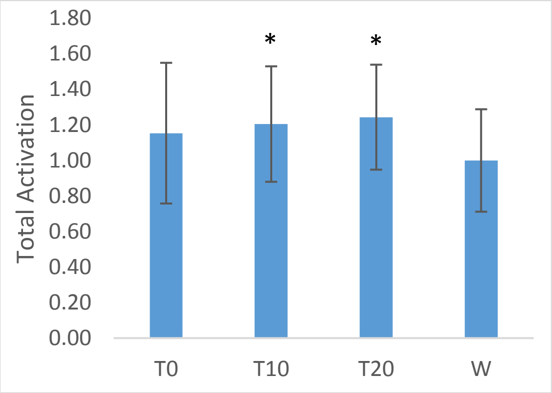


*Figure 4.10 - Ratio of total muscular activation (n=15) of the Deltoid Medius when performing a Lateral Raise under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from W.*

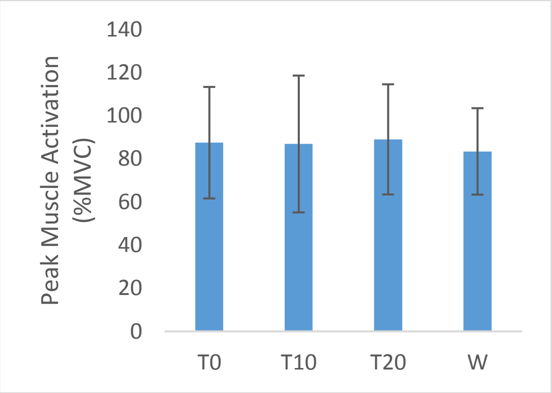


Figure 4.11 - Mean ± SD (n=15) peak muscular activation of the Deltoid Medius when performing a Lateral Raise under four different conditions (T0,T10,T20,W).

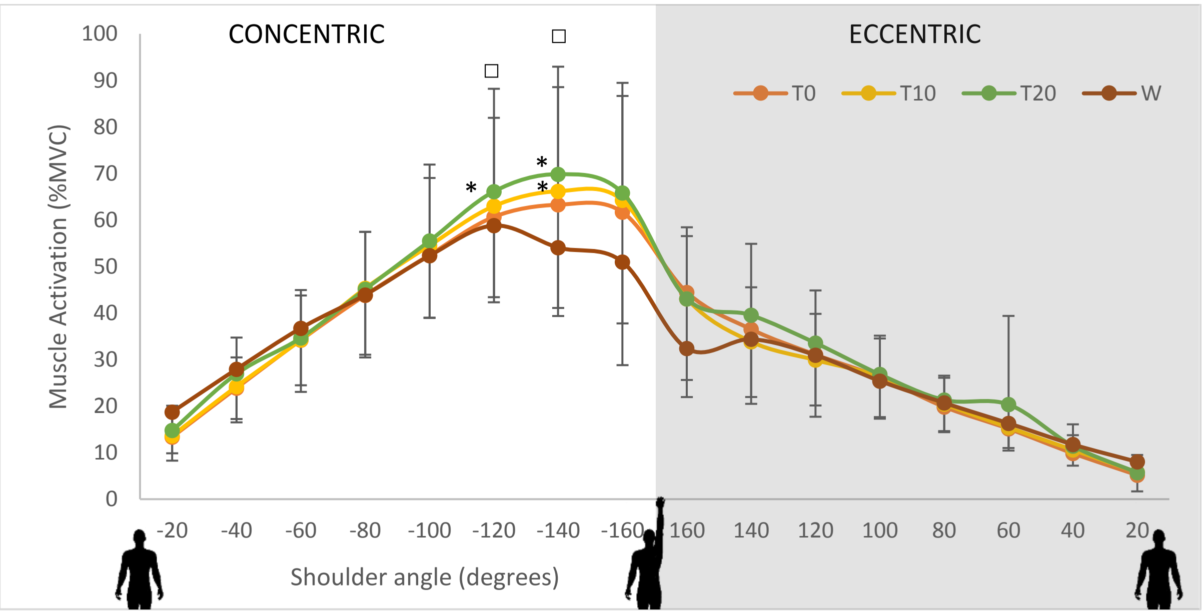


*Figure 4.12 - Mean ± SD muscular activation (n=17) of the Deltoid Medius per every 20° of ROM, throughout the entire range of motion of a Lateral Raise, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition; □ Significant difference (p<0.5) among tube conditions.*

4.4.2.2 Trapezius Descendens

During the lateral raise, both total activation (Figure 4.13) and peak activation (Figure 4.14) of the trapezius showed a trend towards higher levels in all elastic conditions with respect to W, and increased with initial tube stretch, but only reached statistical significance for total activations (p=.016). While all conditions followed similar activation patterns (Figure 4.15), T20 elicited the highest trapezius activation (p=.002; p=.037) in both the concentric and eccentric phases.

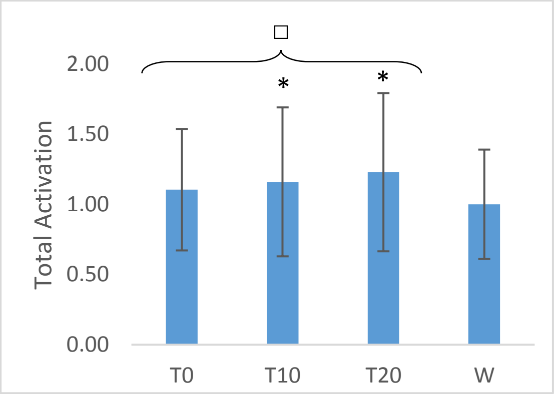


*Figure 4.13 - Ratio of total muscular activation (n=17) of the Trapezius Descendens when performing a Lateral Raise under four different conditions (T0,T10,T20,W). □ T20 significantly different (p<.05) than T0,T10. * W significantly different (p<.05) than T10,T20.*

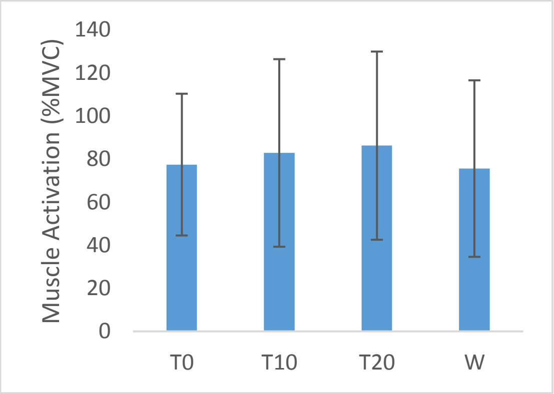


Figure 4.14 - Mean ± SD peak activation (n=17) of the Trapezius Descendens when performing a Lateral Raise under four different conditions (T0,T10,T20,W).

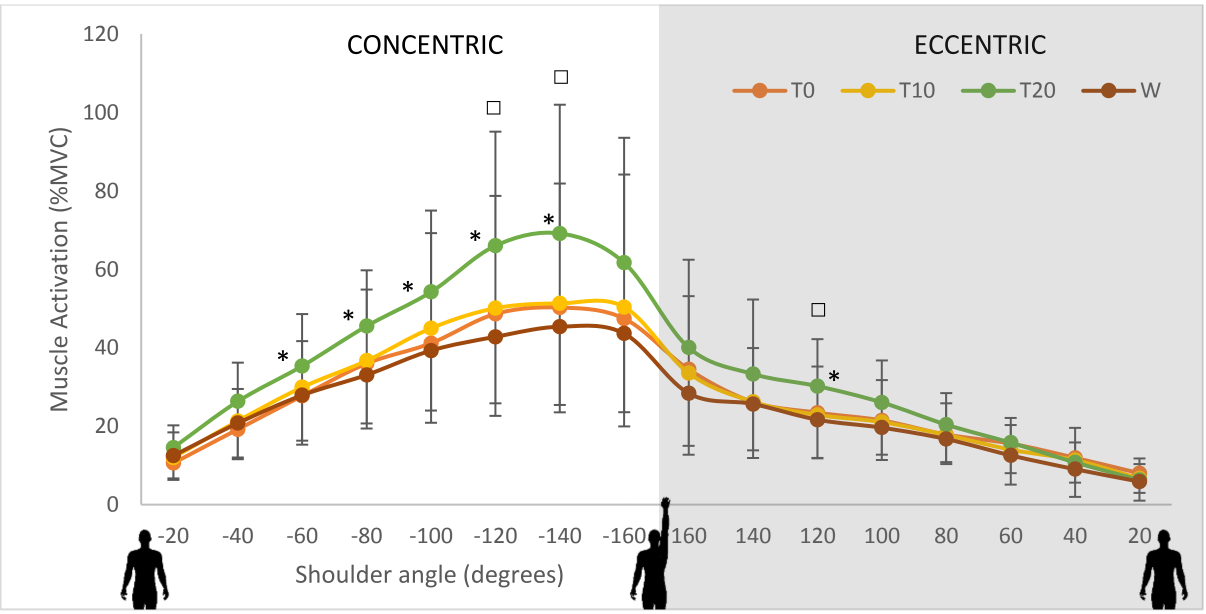


*Figure 4.15 - Mean ± SD muscular activation (n=17) of the Trapezius Descendens per every 20° of ROM, throughout the entire range of motion of a Lateral Raise, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition; □ Significant difference (p<0.5) among tube conditions.*

4.4.2.3 Biceps Brachii

During the lateral raise, both total (Figure 4.16) and peak activation (Figure 4.17) of the biceps were significantly higher in all elastic conditions with respect to weight resistance (p≤.017; p≤.028). All elastic conditions elicited a significantly higher activation than W at 140° to 160° of both the concentric (p<.001) and eccentric (p=.009) phases (Figure 4.18).

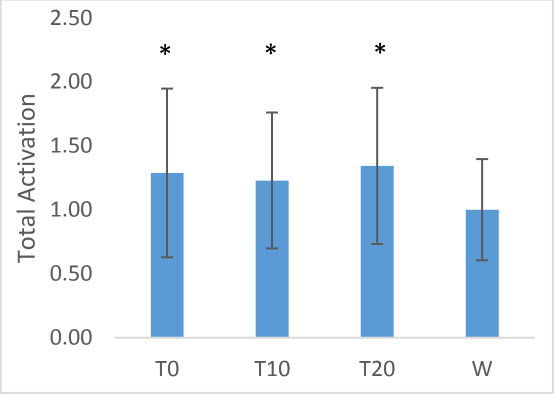


*Figure 4.16 - Ratio of total muscular activation (n=17) of the Biceps Brachii when performing a Lateral Raise. * Significant difference (p≤.028) from W.*

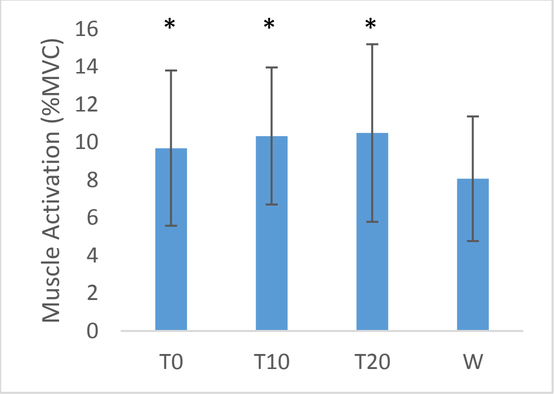


*Figure 4.17 - Mean ± SD peak activation (n=17) of the Biceps Brachii when performing a Lateral Raise under four different conditions (T0,T10,T20,W). * Significant difference (p≤.017) from W.*

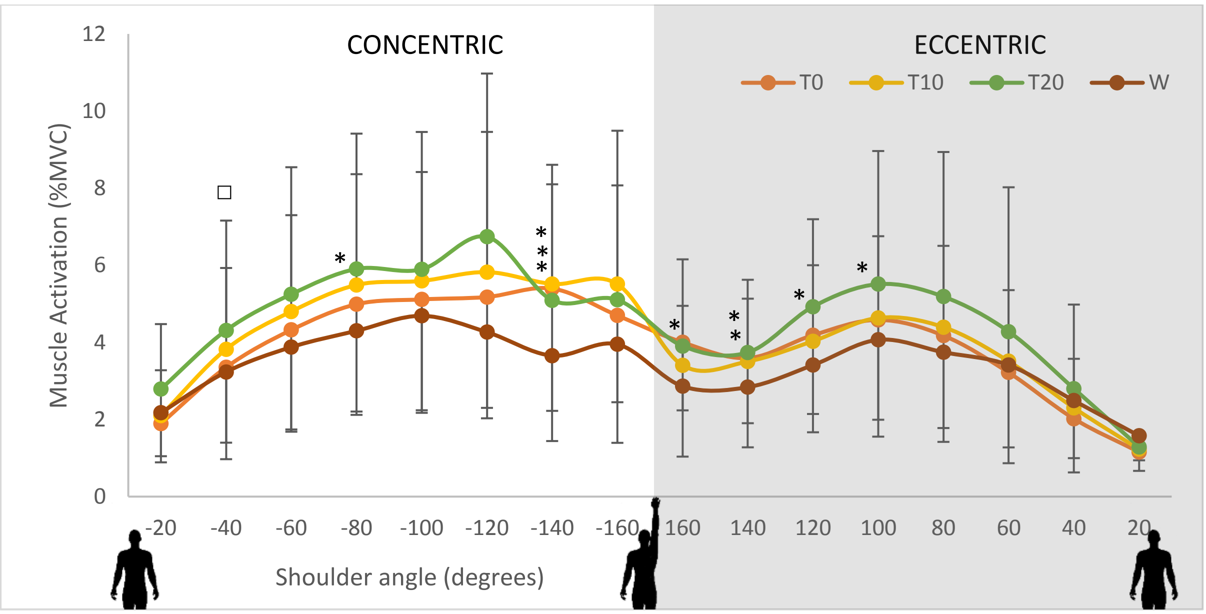


*Figure 4.18 - Mean ± SD muscular activation (n=17) of the Biceps Brachii per every 20° of ROM, throughout the entire range of motion of a Lateral Raise, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition; □ Significant difference (p<0.5) among tube conditions.*

4.4.2.4 Triceps Brachii

During the lateral raise, there was no significant difference in triceps activation between conditions. Trends of increased activation are perceptible in all elastic conditions compared to W for total activation (Figure 4.19), peak activation (Figure 4.20) and throughout most of the concentric phase (Figure 4.21), although none of these values reached statistical significance due to the high variance in the data.

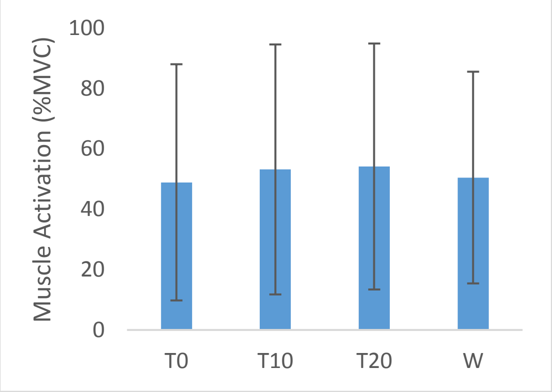


Figure 4.19 - Ratio of total muscular activation (n=15) of the Deltoid when performing a Lateral Raise under four different conditions (T0,T10,T20,W).

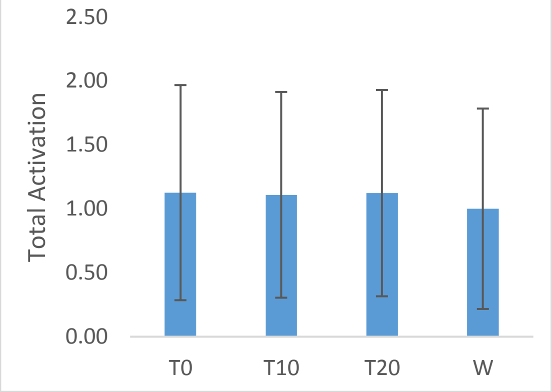


Figure 4.20 - Mean ± SD peak activation (n=15) of the Triceps Brachii when performing a Lateral Raise under four different conditions (T0,T10,T20,W).

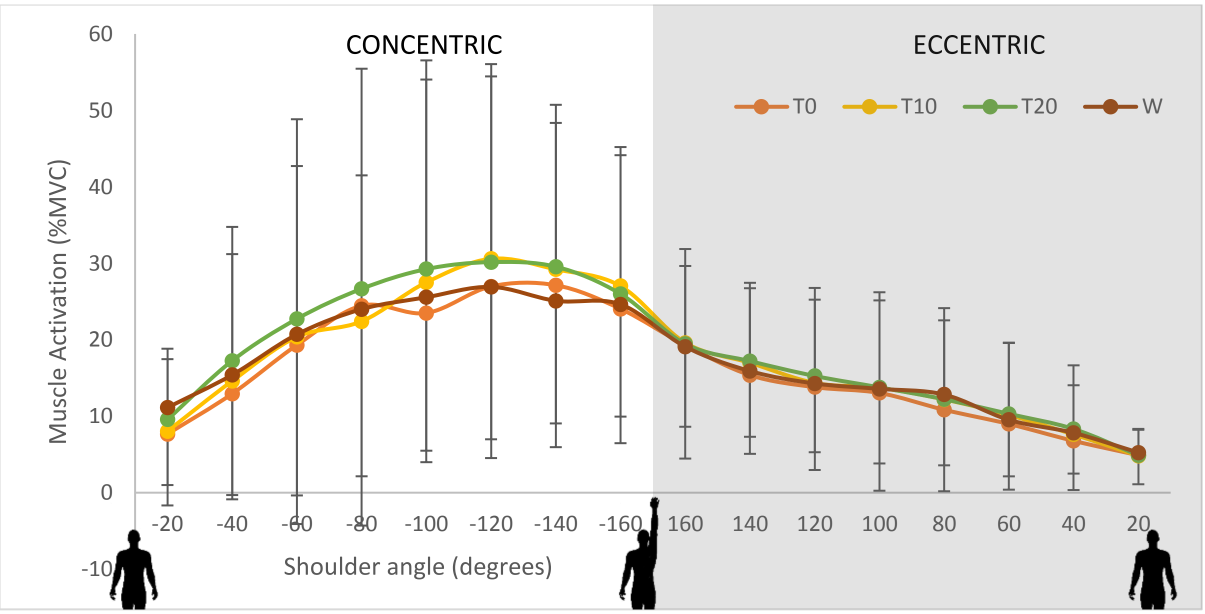


Figure 4.21 - Mean ± SD muscular activation (n=17) of the Triceps Brachii per every 20° of ROM, throughout the entire range of motion of a Lateral Raise, under four different conditions (T0,T10,T20,W).

4.4.3 Leg Extension

4.4.3.1 *Rectus femoris*

During the leg extension, total activation of the rectus femoris (Figure 4.22) was significantly (p=.043) lower than W for T10 and T20, while peak activation (Figure 4.23) was significantly lower (p<.001) than W for all elastic conditions. Compared to W, T0 elicited a significantly lower activation of the rectus femoris at the end of the ROM for both the concentric (p=.022) and eccentric (p=.016) phases (Figure 4.24); the other tube lengths showed a similar trend with alpha reaching near significance level (p=.06). There was also a significant difference between tube conditions, where T20 elicited higher activation than the other tube conditions throughout the concentric phase, with it being significantly higher (p<.05) than T0 at the beginning and end of concentric ROM (Figure 4.24).

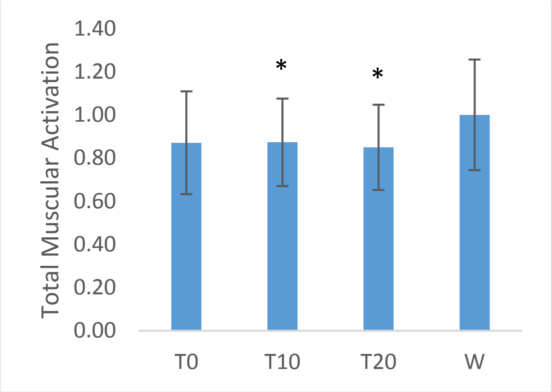


*Figure 4.22 - Ratio of total muscular activation (n=13) of the Rectus Femoris when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference between W and T10,T20.*

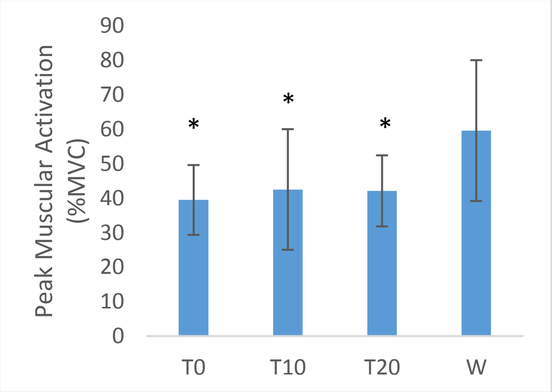


*Figure 4.23 - Mean ± SD (n=13) peak muscular activation of the Rectus Femoris when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference between W and all tube conditions.*

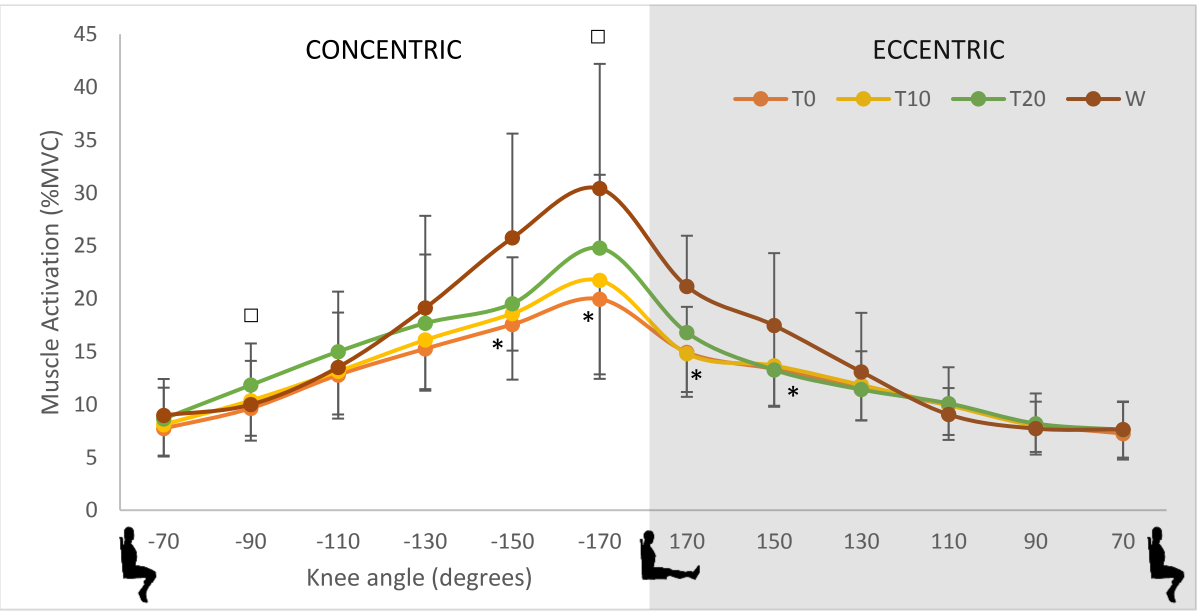


*Figure 4.24 - Mean ± SD muscular activation (n=17) of the Rectus Femoris per every 20° of ROM, throughout the entire range of motion of a Leg Extension, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition; □ Significant difference (p<0.5) between T0 and T20.*

4.4.3.2 Vastus Medialis

During the leg extension, total vastus medialis activation (Figure 4.25) for all elastic conditions was higher than W, reaching significance (p=.044) for T10 and T20, while peak activation (Figure 4.26) for T0 was significantly lower (p=.009) than W. Muscular activation patterns (Figure 4.27) show very similar trends for all four conditions, with figures only reaching significant differences (p=.047) in the concentric phase between elastic conditions, showing an increase in activation with greater initial tube stretch. Weight activation remains lower than all tube conditions during the initial phase of ROM, though not statistically significant.

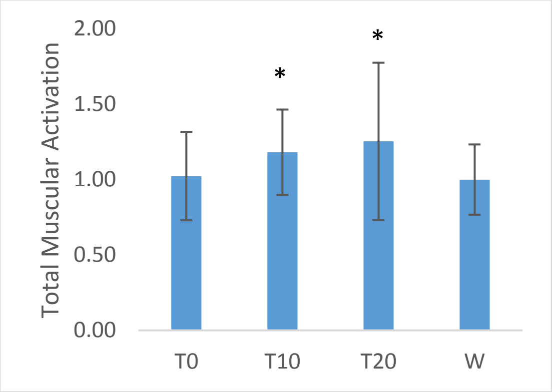


*Figure 4.25 - Ratio of total muscular activation (n=15) of the Vastus Medialis when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference between W and T10,T20.*

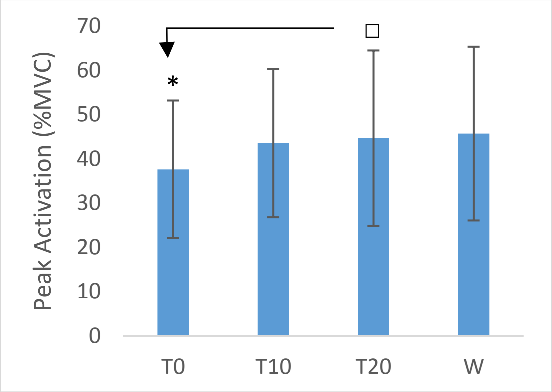


*Figure 4.26 - Mean ± SD (n=15) peak muscular activation of the Vastus Medialis when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference (p=.009) between W and T0; ˉ. □ Significant difference (p=.017) between T20 and T0.*

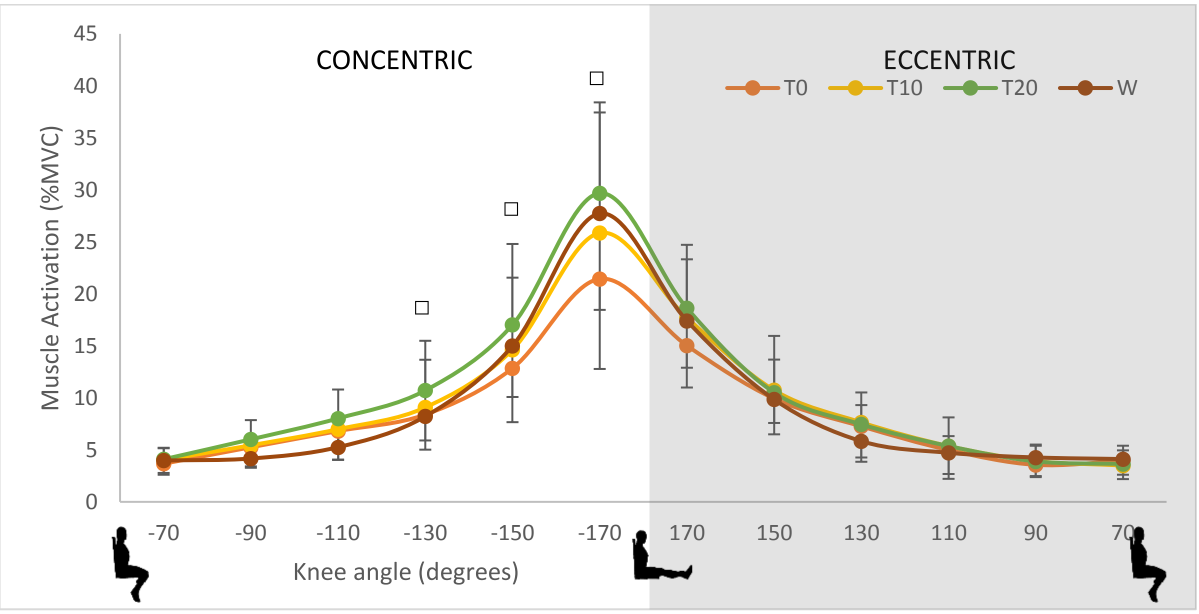


Figure 4.27 - Mean ± SD muscular activation (n=17) of the Vastus Medialis per every 20° of ROM, throughout the entire range of motion of a Leg Extension, under four different conditions (T0,T10,T20,W). □ Significant difference (p<0.5) among tube conditions.

4.4.3.3 Vastus Lateralis

During the leg extension, total vastus lateralis activation (Figure 4.28) was higher in all elastic conditions, reaching significance (p=.05) for T20, while peak activation (Figure 4.29) was not significantly different between conditions. Similar to the vastus medialis, the shape of the muscular activation pattern of the vastus lateralis displays similar trends in all four conditions, but with increasing values for the elastic conditions (Figure 4.30). Activation for T10 and T20 remained significantly higher than W for most of the concentric (p<.001) phase and part of the eccentric phase (p=.012). Activation also increased significantly (p<.05) among elastic conditions with initial tube stretch.

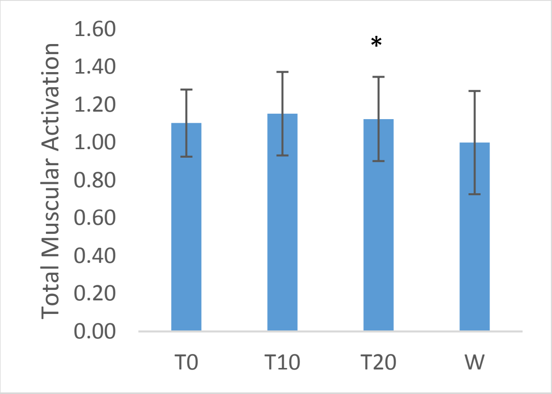


*Figure 4.28 - Ratio of total muscular activation (n=15) of the Vastus Lateralis when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference between W and T20.*

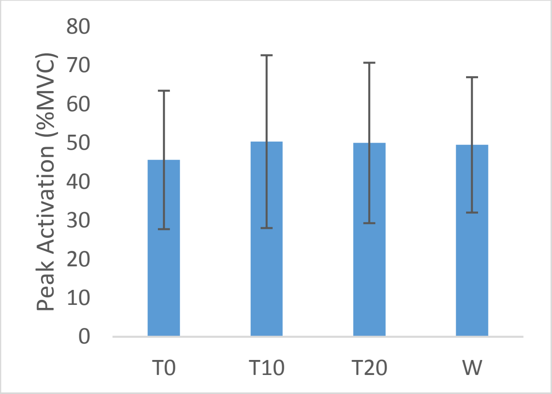


Figure 4.29 - Mean ± SD (n=15) peak muscular activation of the Vastus Lateralis when performing a Leg Extension under four different conditions (T0,T10,T20,W).

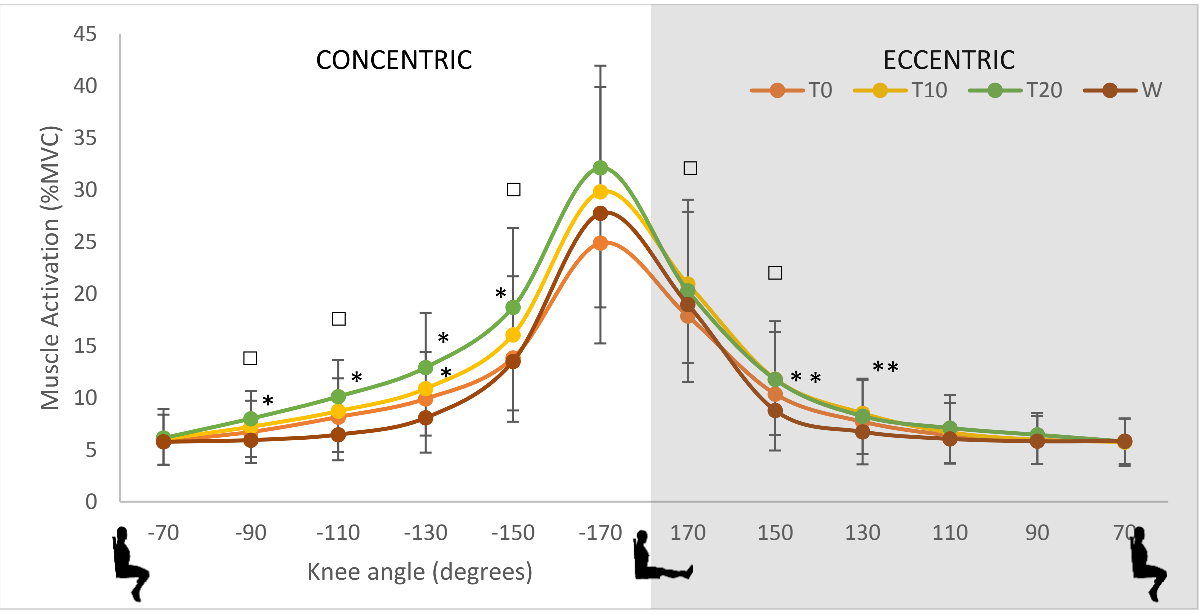


*Figure 4.30 - Mean ± SD muscular activation (n=15) of the Vastus Lateralis per every 20° of ROM, throughout the entire range of motion of a Leg Extension, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition; □ Significant difference (p<.05) among tube conditions.*

4.4.3.4 Biceps Femoris

During the leg extension, both total (Figure 4.31) and peak activation (Figure 4.32) of the biceps femoris showed a tendency to be lower for all elastic conditions compared to W but only reached statistical significance (p=.05) for peak activation under T20. More specifically, muscular activation had a tendency to be lower in all elastic conditions at the start of the ROM of both the eccentric and concentric phases (Figure 4.33), reaching statistical significance for T20 at the end of the concentric phase (P=.015).

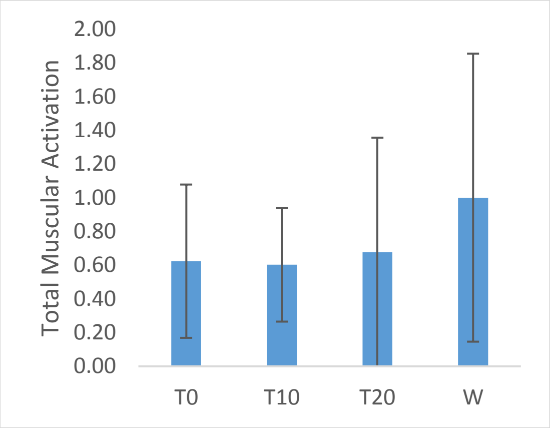


Figure 4.31 - Ratio of total muscular activation (n=15) of the Biceps Femoris when performing a Leg Extension under four different conditions (T0,T10,T20,W).

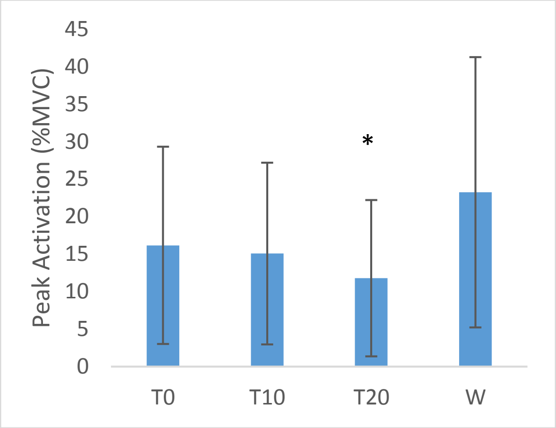


*Figure 4.32 - Mean ± SD (n=15) peak muscular activation of the Biceps Femoris when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference between W and T20.*

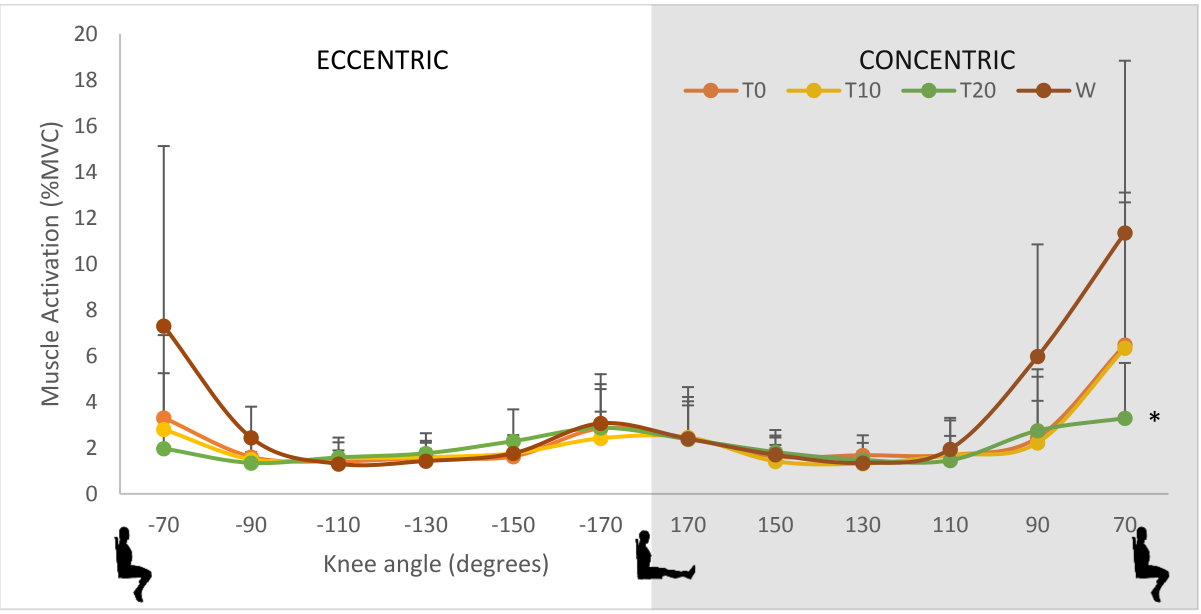


*Figure 4.33 - Mean ± SD muscular activation (n=17) of the Biceps Femoris per every 20° of ROM, throughout the entire range of motion of a Leg Extension, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition.*

4.4.4 Leg Curl

4.4.4.1 Biceps Femoris

During the leg curl, there were no significant differences for total (Figure 4.34) or peak activation (Figure 4.35) of biceps femoris. However, muscular activation patterns show that elastic resistance elicited a significantly lower activation (p<.001) than W at the beginning of the ROM (Figure 4.36).

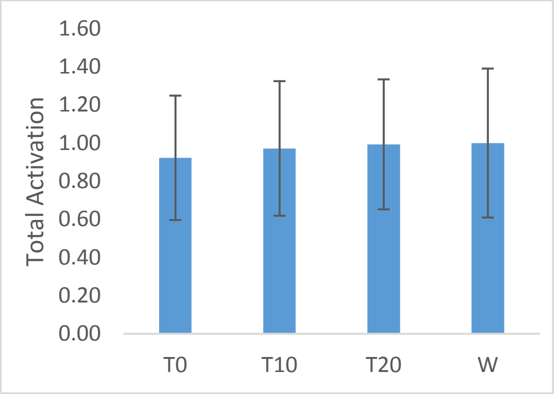


Figure 4.34 - Ratio of total muscular activation (n=15) of the Biceps Femoris when performing a Leg Curl under four different conditions (T0,T10,T20,W).

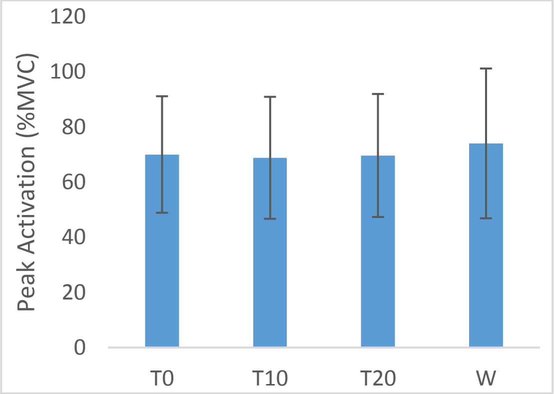


*Figure 4.35 - Mean ± SD (n=15) peak muscular activation of the Biceps Femoris when performing a Leg Extension under four different conditions (T0,T10,T20,W). * Significant difference between W and T20.*

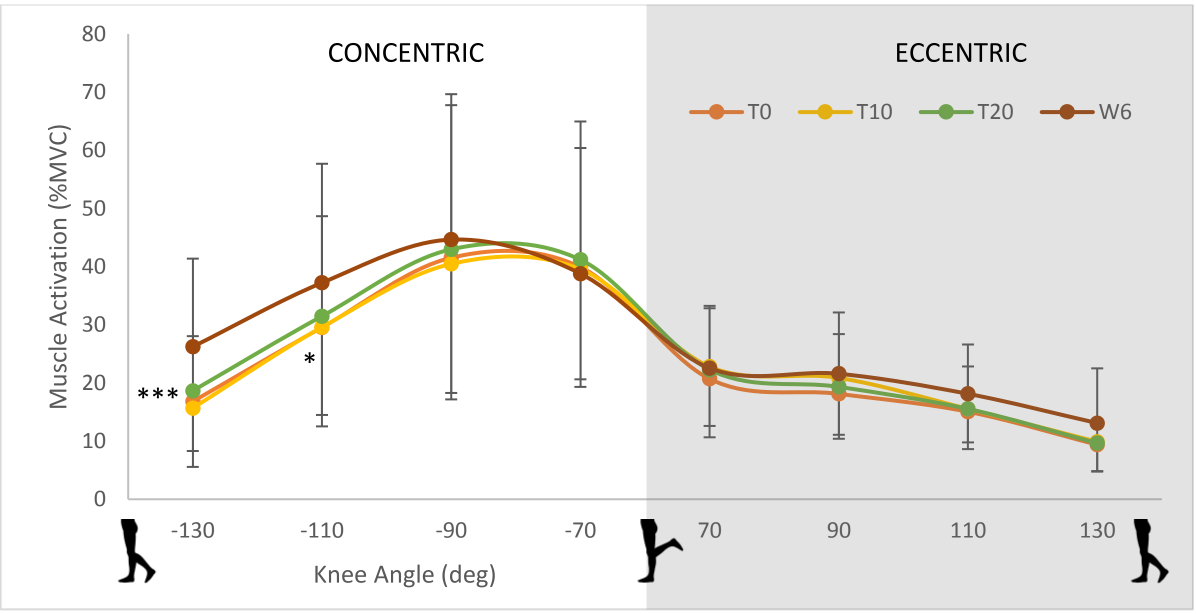


*Figure 4.36 - Mean ± SD muscular activation (n=17) of the Biceps Femoris per every 20° of ROM, throughout the entire range of motion of a Leg Curl, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition*

4.4.4.2 Rectus Femoris

The Rectus Femoris, acting as antagonist muscle of the leg curl, was not perceivably active during the exercise, with EMG values fluctuating by 1% MVC only.

4.4.4.3 Gastrocnemius Lateralis

During the leg curl, total activation (Figure 4.37) of the gastrocnemius was lower in the elastic condition, only reaching significance for T0 against W (p=.049), while peak activation (Figure 4.38) also showed trends of lower values in the elastic condition but did not reach statistical significance. Elastic resistance elicited lower gastrocnemius activation throughout the ROM (Figure 4.), with a statistical significance (p=.038) at the beginning of the concentric phase between T0, T20 and W.

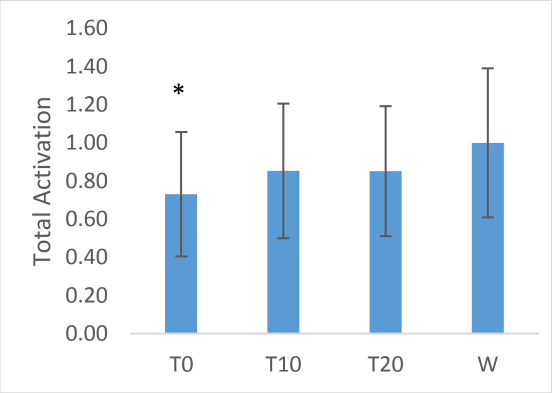


*Figure 4.37 - Ratio of total muscular activation (n=15) of the Gastrocnemius Lateralis when performing a Leg Curl under four different conditions (T0,T10,T20,W). * Significant difference (p=.049) between T0 and W.*

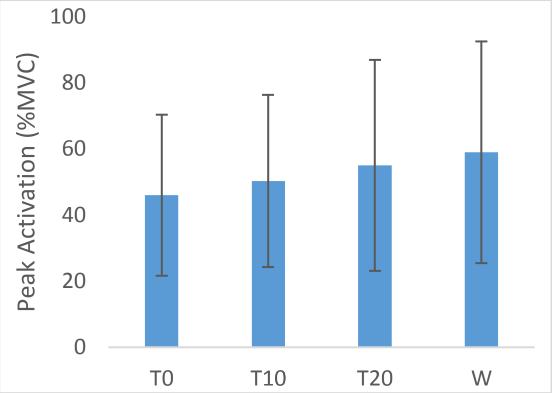


Figure 4.38 - Mean ± SD (n=15) peak muscular activation of the Gastrocnemius Lateralis when performing a Leg Curl under four different conditions (T0,T10,T20,W).

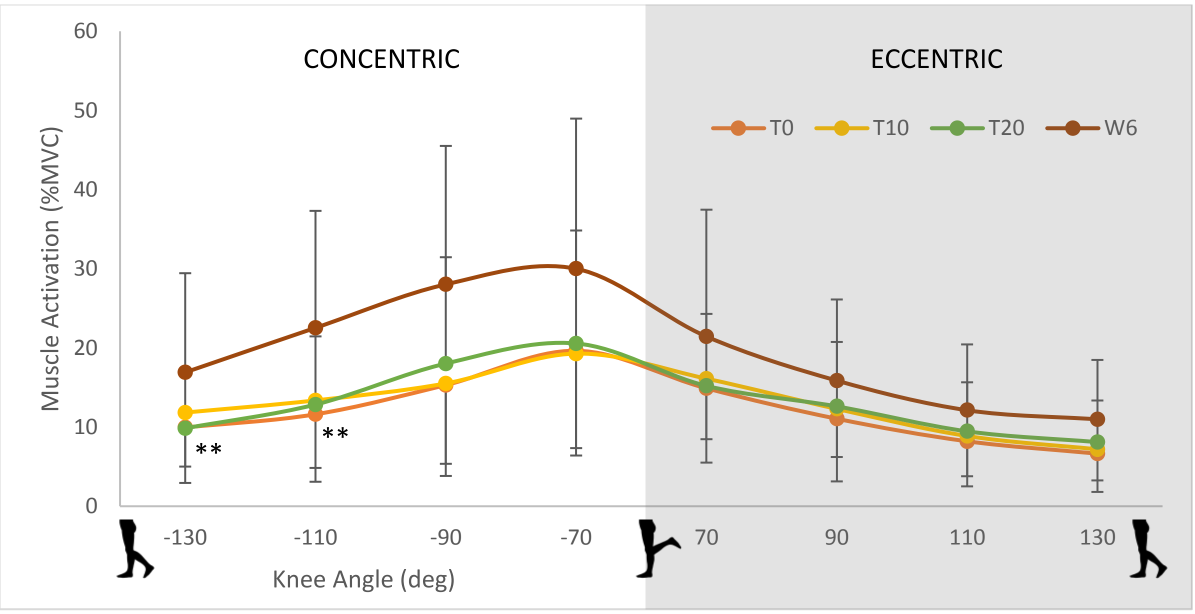


*Figure 4. - Mean ± SD muscular activation (n=17) of the Gastrocnemius Lateralis per every 20° of ROM, throughout the entire range of motion of a Leg Curl, under four different conditions (T0,T10,T20,W). * Significant difference (p<.05) from weight condition.*

4.5 Discussion

The main findings of this study portray a general tendency for elastic resistance to elicit lower muscular activation of the agonist muscles at the initial stages of movement compared to weight resistance and, in contrast, a higher muscular activation at the end of the ROM. Elastic resistance also engaged auxiliary muscles more than weight resistance in the majority of cases, especially with shorter initial tube lengths. The following sections will explore these trends with more detail, relating to the specificity of each exercise.

4.5.1 Tube Lengths

In accordance with previous studies, shortening the initial length of the elastic tubes by only 10% elicited greater total muscular activation compared to unstretched tubes in all exercises (Aboodarda *et al.*, 2013; Aboodarda *et al.*, 2011; Hodges *et al.*, 2006). Aboodarda *et al.* (2011) found that applying a 30% reduction in initial length significantly increased quadriceps activation during a leg extension, although the activation pattern illustrated in their study differed from the data presented here. Aboodarda *et al.*'s (2011) study showed an increased vastus lateralis activation at the beginning of the ROM with no significant effect on peak activation at the end of the concentric phase; in contrast, the data reported here exhibited the opposite, with no difference in activation at the beginning of the ROM, but an increasing difference in activation between all three tube lengths towards latter stages of ROM, which is a closer reflection of Santos *et al.*'s (2009) findings on elastic material properties where applied resistance increases with tube elongation. In this study, one single tube of high stiffness was used, while Aboodarda *et al.* (2011) combined several lighter tubes in parallel in order to achieve the desired level of resistance. Considering that stiffer tubes cause steeper increments in tension than light tubes, using several lighter tubes in parallel would have increased the load across the ROM in Aboodarda *et al.*'s (2011) study, while reducing the initial length of the stiffer tube in this study caused an exponential increase with greater strains. Therefore, shortening the elastic tubes increased peak EMG at the end of the ROM in most scenarios, although it did not affect muscular activation at the beginning of ROM. This indicates that shortening the initial length of the tube remains a good strategy for increasing resistance for rehabilitation training, where a gradual increase in activation is preferred. In contrast, based on Aboodarda *et al.*'s (2011) observations, it may be preferable to use several tubes in parallel, rather than one stiff shortened tube, in order to increase resistance at early stages of the concentric action, increasing time-under-tension and reducing the variability of muscular activation throughout the ROM.

By analysing a variety of initial tube lengths, it was anticipated that one of the lengths could have been chosen as the most comparable to the weight condition, however the findings described hereafter portray some substantial differences between muscular activation signals and muscle recruitment elicited by elastic and weight resistance which will lead to the conclusion that elastic and weight resistances are complementary rather than comparable. Given the variety of responses across exercises, it was therefore not possible to determine a set tube length to recommend as a "best comparison" to weight resistance. Findings between elastic conditions do however indicate that reducing the initial length of tubes can be an effective method for increasing load during elastic training.

4.5.2 Agonist Muscles

Differences in peak and total activation of the agonist muscles varied between exercises and will therefore be discussed separately.

4.5.2.1 Bicep curl

Peak bicep activation was equal under both resistances but occurred at the end of the ROM in the elastic conditions (30°±10 elbow angle) and at mid ROM (80°±10) in the weight condition. These observations reflect in part the findings of Aboodarda *et al.* (2013), who also observed higher biceps activation at the end of the ROM with elastic resistance compared to weights but found that peak activation occurred at mid ROM under both conditions. It is worth noting that Aboodarda's study averaged muscular activation over larger sections of ROM (three sections in Aboodarda's study vs seven sections in this study), which may have contributed to the difference in peak findings. The activation patterns observed here seem to more accurately reflect previously observed curves of external applied forces where, due to mechanical advantage, the isotonic load applied by free weights decreases at the end of the ROM (Aboodarda *et al.*, 2013) while elastic resistance increases with tube elongation (Santos *et al.* 2009), applying greater tension at the end of the ROM.

Theoretical calculations of required muscle action throughout the concentric action of the bicep curl indicate that agonist activation should increase exponentially under the elastic condition and plateau with weight resistance (Table 4.2). Experimental data, however, present a peak in bicep activation under elastic resistance and a drop with weight resistance, which is inconsistent with the mentioned calculations (Figure 4.3). The calculations are a gross oversimplification of the actual forces acting on the joint during a bicep curl. This is, in part, due to using an estimation of biceps brachii moment arms in the force calculations, which are not measurable in vivo and were therefore taken from cadaveric studies (Pigeon *et al.*, 1996; Murray *et al.*, 1995). Other factors that limit the validity of these calculations include the omission of synergist muscle contribution, such as that of the brachialis and brachioradialis, and the individuality of human anatomy. Nontheless, the differences between the experimental data and the estimation are excessive, and probably related to actual changes in muscle contribution rather than computational constraints. Three factors possibly contributed to the increased agonist activation at the end of the ROM in the elastic condition: the material properties of the elastic tubes, the unpredictability of a variable force in both magnitude and direction and a change in technique with elastic resistance.

As elastic materials stretch, they store energy which drives them to return to their initial length, generating a resistance that increases with elongation (Santos *et al.*, 2009). This property generates a force that not only resists against the joint movement but also constantly pulls back, effecting a concentric/eccentric feedback loop of muscle action, where the agonist muscle is contracting to flex the joint (concentric) and at the same time resisting the increasing elastic tension (eccentric). This variability in the applied force is incongruent with accustomed movements where resistance is typically isotonic, making it highly unpredictable for the neuromuscular system. Under elastic resistance, the applied force varies in both magnitude and direction throughout the movement, requiring a greater activation of agonist muscles and the recruitment of auxiliary muscles to stabilise the joint.

Lastly, it was evident through 3D motion analysis that most participants changed their technique when performing bicep curls with elastic tubes as opposed to with weights: at the end of the ROM, participants had a tendency to lift their elbows significantly more in the elastic condition (Table 4.1). While lifting the elbow in order to stretch the tube further, the shoulder joint was flexed by action of the biceps and deltoid muscles, which were in fact both significantly more active at the end of the ROM in the elastic condition (Figure 4.3, Figure 4.9). The biceps brachii originates at the scapula and is, therefore, a weak contributor to shoulder flexion. Further to being at a disadvantageous length when the elbow is flexed due to a high overlap of contractile filaments, the lifting of the elbow would have also necessitated a greater biceps activation in order to match the required force output at this stage of contraction. As for the drop in muscle activation in the weight condition at the end of the ROM (Figure 4.3), 3D motion analysis showed that participants also lifted the elbow when using dumbbells, but only enough to bring the forearm nearly perpendicular to the line of gravity (9°±15 of inclination from the vertical) which produced a mechanical advantage by significantly reducing the moment arm, hence requiring less force from the biceps muscle to sustain the weight.

Finally, despite the striking differences in biceps activation in the concentric phase, there were no significant differences, and no visible trends, between the elastic and weight conditions in the eccentric phase of the bicep curl. Both resistance methods elicited very low activations throughout the eccentric phase (ranging from 10 – 20 %MVC) with a tendency to increase with initial tube stretch, yet not reaching statistical significance. In contrast, Aboodarda *et al.* (2013) reported a significantly higher activation with weights at the end of the eccentric phase. Despite the lack in statistical significance, the data reported here also shows trends of decreasing activation with tubes, as the strain of T0 and T10 became negligible at the end of the eccentric phase, and increasing activation with weights up to 130° ± 10 elbow angle, with a subsequent drop at 150° ± 10 elbow angle where the participant may have briefly rested the arm before the next repetition. Aboodarda *et al.* (2013) restricted the ROM to 140° elbow angle, which could have caused the difference in statistical findings. Furthermore, the extention phase of a bicep curl is largely governed by grativational forces, therefore requiring little action of the agonist muscle with low loads, unless a deceleration of movement is required. The low velocity of the task, and the higher load with stretched tubes (T20), would have required some contribution from the biceps, resulting in a slightly higher activation in this condition. It can be therefore inferred that, had the movement velocity of the extention phase been higher, the biceps activation would have probably remained negligible in all elastic conditions. This indicates that, due to its decreasing force throughout the extension phase, elastic resistance may not be appropriate for eliciting eccentric activation of the agonist muscles.

4.5.2.2 Lateral Raise

The agonist muscle of the lateral raise (deltoid), displayed similar behaviour to that of the bicep curl, with a peak in activation at the end of the ROM in the elastic condition and contrasting drop ($p<.05$) in the weight condition (Figure 4.12). These findings add to those of Andersen *et al.* (2010) who studied a lateral raise to 90° shoulder abduction and found no significant difference in deltoid or trapezius activation. At 90° the moment arm is at its maximal length during the exercise and the resistive force of the dumbbell is therefore at its highest. In this study, deltoid activation did not exhibit differences in activation up to 90° abduction either, yet shoulder abduction reached 180° where the arm is at a near-vertical position at full ROM, hence gaining mechanical advantage in the weight condition by reducing the moment arm to a minimum. Similar to the bicep curl, the direction of the applied elastic tension was not vertical, and therefore applied greater load to a contracted deltoid which was at a disadvantageous sarcomeric overlap, leading to an increase in activation at the end of the ROM under elastic resistance to match the required force output. Therefore, significant differences in agonist and synergist activation in this study occurred at shoulder angles above 100°, which were not examined by Andersen *et al.* (2010), hence the difference in the findings.

4.5.2.3 Leg Extension

The agonist muscle of the leg extension (rectus femoris) responded differently to the other exercises. The elastic and weight conditions portrayed similar shapes of the muscular activation curve of the agonist and synergist movers, all exhibiting peak activation at the end of the ROM in all conditions. In a similar study, however, Jakobsen *et al.* (2012) reported peak rectus femoris activation at about 135° internal knee angle, and vastus lateralis and medialis peak activation at about 155°, substantially differing from the findings presented in the current study, where all three muscles exhibited peak activation at about 170° of knee extension with equal angular velocities. Both studies implemented equal angular velocities (60deg·s^{-1}), ruling out the possibility that this variable would have affected the results. This substantial difference in the location of peak agonist and synergist activation is likely due to differing positioning of the anchor points of the elastic tube relative to the ankle strap. In the current study, the elastic tube pulled on the ankle at a 20° angle with respect to the extended leg at the end of the concentric phase, while Jakobsen *et al.*'s (2012) set-up suggests a much smaller angle of pull at full leg extension given a larger distance between the tube ground anchoring point and the participant. The smaller angle of force application would have significantly reduced the moment arm of the elastic load, offering mechanical advantage to the quadriceps muscles at final phases of the ROM, hence requiring less activation. The longer distance, and hence longer tube, in Jakobsen *et al.*'s (2012) study would have also implied a lesser change in percentage elongation, causing smaller increments in load towards final phases of movement. These differences underline the importance of considering exercise set-up and tube anchoring points during elastic training, as the positioning of the tubes can greatly affect patterns in muscular activation throughout the full ROM, further influencing training adaptations at both performance and architectural level.

Furthermore, in accordance with findings by Matheson *et al.*, (2001), despite having selected a tube of equivalent applied load to the weight condition (Page *et al.*, 2000), total and peak rectus femoris activation were lower under elastic resistance with respect to weights. This can also be explained by differences in directions of applied force between the two resistance types: while the load of the ankle weight was perpendicular to the moment arm at full leg extension, the elastic tubes pulled back on the ankle at a 20° angle. Therefore, despite the increased load of the tubes at the end of the ROM, the direction of pull gave mechanical advantage to the agonist muscle in the elastic condition, requiring less activation than expected.

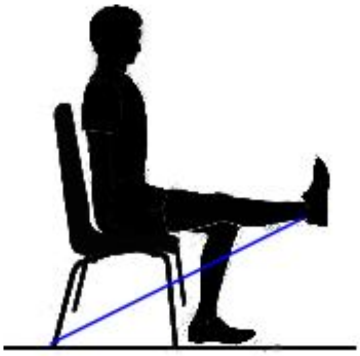


Figure 4.39 – Set up of a leg extension with elastic resistance.

4.5.2.4 Leg Curl

The agonist muscle of the leg curl (biceps femoris) also exhibited similar trends to the bicep curl and lateral raise, but lacked significant difference at latter stages of movement, which was due to a smaller ROM compared to other exercises (Table 3.3). This led to a smaller change in tube elongation, effecting equal loading at the end of the ROM between weights (2.3kg) and tubes (2.6kg equivalent).

4.5.2.5 Overview of agonist muscles

The elastic force generated by tubes increases with stretch (Santos *et al.*, 2009) and therefore elicits higher muscular activation at the final phase of movement, while the opposite is generally true for weights. Overall, the exercises where the direction of the applied force was nearly parallel between conditions (bicep curl, lateral raise and leg curl) exhibited a peak in agonist activation in all elastic conditions at the end of the ROM, and a contrasting drop in activation with weight resistance at the same joint angles.

An example that illustrates the importance of considering directions of applied force is found in Simoneau *et al.*'s, (2001) research. They found opposing resistance curves generated by elastic tubes and dumbbells when the participant performed an elbow flexion while laying supine. In the aforementioned study, the tubes were attached below the participant's feet, rendering the direction of elastic force perpendicular to that of the dumbbells (where weight is dependent on gravity), hence the difference in patterns of resistive torque. Simoneau *et al.*'s, (2001) findings underline the importance of considering the point of force application relative to the exercising joint when comparing elastic and weight loads; where weight resistance is dependent on gravity, while elastic tension is not. The implications of this are clearly identified in this study, in the different outcomes between the standing exercises with a near-vertical positioning of the tubes (bicep curl, lateral raise and leg curl), and the sitting exercise (leg extension), where the application of elastic tension was nearly perpendicular to the line of gravity. It must also be considered that the standing exercises in this study were executed with a full ROM, where the exercising limbs finalised the movements in a near-vertical position, substantially reducing moment arms at latter stages of movement, giving the agonist muscle a greater mechanical advantage in the weight condition.

It can therefore be speculated that, when moving throughout the entire ROM and when the directions of applied force are comparable, either method could result in different, possibly complementary, muscular adaptations. Researchers have in fact suggested that a combination of weights and elastic tubes may provide more effective strength and power training programmes than using one method alone, as this would enable adaptations to occur throughout the entire length of the muscle (Frost *et al.*, 2010; Wallace *et al.*, 2006; Behm *et al.*, 1991).

4.5.3 Auxiliary Muscles

As for synergists and stabilizer muscles, these were generally more active with elastic resistance. During the bicep curl, the increased deltoid activation at smaller elbow angles (Figure 4.9), coupled with an increased mediolateral movement of the elbow (Table 4.1), suggest that the deltoid was implemented in stabilizing the shoulder when under elastic resistance. In addition to mediolateral stabilization, the deltoid exerted agonist action in lifting the elbow at the end of the ROM due to an instinctive change in technique in the elastic condition, further contributing to its increase in activation

(Section 4.5.2.1). It must however be noted that, in this study, the electrode was positioned on the medial deltoid, which is more responsible for shoulder abduction rather than flexion. Had the electrode been positioned on the anterior portion of the deltoid for the bicep curl, the readings would have been different, probably showing greater activation during its agonist action on shoulder flexion at the end of the ROM. Moreover, there were no significant trends in the eccentric phase to suggest any effect of resistance method on deltoid activation during the bicep curl. Similar to the biceps muscle, deltoid activation decreased throughout the entire eccentric phase, dropping to lower values than in the weight condition at the end of the ROM. This response is related to the decrease in load applied by the elastic tubes as they recoil, although the lack in statistical significance indicates that this may not be a relevant difference at low loads. The extension phase of the bicep curl is governed by gravitational forces and, with low loads, required little contribution from auxiliary muscles. Higher loads may possibly lead to significant differences in these responses and should be investigated further.

During the lateral raise, although the difference was statistically significant only for the biceps, both the biceps and triceps were also more active under elastic resistance, playing a stabilizing role at both the shoulder and the elbow. The biceps also exhibited higher activations throughout the eccentric phase in the elastic condition, although this was not related to a specific role in eccentric action, but rather to a greater overall contribution of the muscle to joint stability in the elastic condition, which was translated to a significantly higher total EMG.

During the leg extension, in contrast with Matheson *et al.'s* (2001) findings, total vastus lateralis and vastus medialis activation were higher under elastic resistance despite the lower activation of the rectus femoris. In this study, the greater total activation of synergist muscles in the elastic condition was not related to a higher peak activation (which was not significantly different between methods), but rather to a greater contribution of these muscles throughout both the concentric and eccentric phase when under elastic resistance (Figure 4.27, Figure 4.30), indicating that elastic resistance elicits the recruitment of secondary muscles to stabilize joint movement throughout the ROM. Furthermore, at equal agonist activation, the contribution of the synergist muscles would have been substantially greater in elastic condition, rendering this method of resistance more appropriate than weights for engaging secondary muscles during strength training. As for the occurrence of peak activation of synergist muscles, Jakobsen *et al.* (2012) reported opposing curves between elastic resistance and a knee extension gym machine, where the former elicited peak synergist activation towards the end of the ROM (155° internal knee angle) while the latter elicited peak synergist activation at earlier stages of ROM (110°). The differences in activation patterns in Jakobsen *et al.*'s (2012) study lie in the method of application of force in the two conditions. With gym machines, the momentum generated by an initial muscle action aids the movement of the machine's lever arm around its axis of rotation while, contrastingly, the increasing tension of the elastic tube overcomes this momentum, requiring an exponential increase in muscular activation in order to complete the full ROM. In the current study, the shape of the activation patterns was equivalent in both elastic and weight conditions, with peak agonist and synergist activation both occurring at the end of the ROM (170°) where the resultant torque applied by either load is at its highest due to the moment arm reaching its maximum length in the weight condition and the tube reaching its greatest elongation in the elastic condition. Based on these observations, it can be concluded that, with the current set-up, free weights and elastic tubes both elicit peak muscular activation at full ROM during a leg extension, although the elastic resistance offers the added benefit of engaging synergist muscles more than the weights.

Free weights carry a constant load and are dependent on gravity, therefore applying a constant force that is predictable and to which most individuals are accustomed. In contrast, the line of pull of elastic tubes changes in its direction relative to the point of application throughout the ROM, while the magnitude of applied tension also changes with its elongation, generating a resistance that is variable in both magnitude and direction. The unpredictability of elastic resistance therefore necessitates a greater stimulation of the neuromuscular system and the engagement of auxiliary muscles to stabilize joint movement throughout the ROM. The external resistance applied by elastic tubing therefore destabilizes joint movement, eliciting a greater activation of auxiliary muscles, hence suggesting that elastic resistance may be more appropriate than weights for proprioceptive training. The greater recruitment of synergist and stabilizer muscles also suggests that elastic training may be more effective than weight training in engaging secondary muscles, therefore strengthening joints and reducing the risk of injury.

4.5.4 Antagonist Muscles

It can be speculated that, given the exponential increase in tension of elastic tubing, muscles concurrently contract to flex the joint and resist against an increasing recoil force that pulls to extend the joint. This mechanism may have contributed to an increase in agonist-antagonist co-activation at latter stages of movement, which is clearly visible with the triceps brachii at 30° elbow flexion during the bicep curl (Figure 4.5). Considering that all three elastic conditions portrayed the exact same shape in activation patterns, with peak values increasing in direct relation to tube length, it is highly unlikely that the occurrence of peak activation at the end of its eccentric action would have been a coincidence. In addition, repeatability tests in Section 3.3.4.4 portray a small typical error value (0.28) for this portion of the ROM in the weight condition, suggesting that, despite the high standard deviations which are indicative of a high inter-subject variance in the amplitude of the EMG signal, the shape of the muscular activation patterns accurately reflects changes in activation throughout the ROM. Therefore, even though differences in triceps peak activation did not quite reach statistical significance (p=.08), given the inherently high variability of EMG data, it is worth considering the visible trends exhibited by this muscle in its antagonist function during the bicep curl. This strengthens the notion that elastic resistance training may be more effective at promoting joint stability than weight training by increasing muscle recruitment during exercise, suggesting an effective application of elastic training in both the rehabilitation and prevention of injuries.

During the leg extension, biceps femoris activation was lower under elastic resistance due to differing directions of applied force at knee angles smaller than 90° (Figure 4.39). When the knee passed the vertical line, the direction of the force applied by weight resistance pulled down on the ankle, extending the knee, while the force applied by the elastic tube pulled back on the ankle, flexing the knee. Therefore, given the set-up used in this study, at flexed knee angles the biceps femoris had to counteract a vertical pull of the ankle weight with a concentric action, which was not necessary in the elastic condition.

Antagonist activation was therefore highly affected by the positioning of the tubes relative to the exercising limb. These findings reveal the importance of considering tube anchor points when setting up exercises with elastic resistance, where tubes that are somewhat parallel to the line of gravity may elicit an enhanced activation of antagonist muscles with respect to weights.

4.5.5 Length-Tension Relationship and Implications for Injury Risk

Setting aside differences in exercise set up and magnitudes of activation, it can be established that, as a general rule, elastic resistance elicits the greatest muscular activation at the end of the ROM. Considering the length-tension relationship of skeletal muscles, and their adaptability along the length-tension relationship curve (Rassier *et al.*, 1999), it is important to take account of the effects of implementing programmes that include the use of elastic resistance training. Differing muscular responses throughout the ROM have crucial effects on long term adaptations of the muscle's architecture, where long term strength training that focuses muscular exertion at stretched muscle lengths has been found to casue an increase in the number of in-series sarcomeres per fibre, rendering it stronger, while the opposite is true for exerting muscles at short muscle lengths (Alegre *et al.*, 2014; Brughellli *et al.*, 2010; Herzog *et al.*, 1991; Lynn and Morgan, 1994). These adaptations affect the muscle's behaviour along the length-tension relationship curve making it more, or less, prone to injury (Timmins *et al.*, 2016).

A recently injured muscle may benefit from the gradual increase in load offered by elastic resistance, where the application of force at contracted muscle lengths can provide a safe method of resistance training without overly exerting the muscle at stretched positions. However, injured muscles exhibit shortened muscle fibres with a reduced number of in-series sarcomeres after healing (Timmins *et al.*, 2015), and would likely benefit from training methods that exert the muscle at stretched lengths in order to influence an increase in the number of sarcomeres, and consequent reduction in their lengths, to prevent further injuries. For example, Proske *et al.* (2004) found that hamstring peak force shifted to significantly shorter muscle lengths after injury. In this study, the leg curl (Section 4.4.4) exhibited higher biceps femoris activation at long muscle lengths with weights rather than with elastic resistance (Figure 4.36). Therefore, considering Proske *et al.*'s (2004) findings, it can be suggested that a healed hamstring may be more appropriately rehabilitated with weighted resistance rather than an equivalent elastic resistance in order to produce strength adaptations at long muscle lengths, reducing the risk of further injury. Alternatively, the initial length of the elastic tube could be highly reduced to apply greater force at the beginning of the movement, and the ROM could be reduced in order to specifically target long muscle lengths. It is worth noting that the tubes' elasticity is not limiting, but rather adds to their versatility in sport specific applications. This study applied the two resistance methods to identical exercises, with same velocity, range of motion and comparative load, but resistances can be adjusted by changing the initial stretch of the elastic tubes, the angle at which the tubes are anchored relative to the limbs, the movement velocity and the ROM of execution.

Elastic training can therefore be considered appropriate for early stages of muscular rehabilitation, where a low, gradually increasing resistance may be safer than weight resistance, but should be coupled with weight training (or adjusted in length) at latter stages of rehabilitation to ensure the preservation of muscular strength at stretched muscle lengths in order to prevent repeated injuries. Elastic resistance may also be appropriate for sport specific training with movements where greater force is required at contracted muscle lengths, such as cycling or boxing, yet it must still be considered that shifting peak force toward more contracted positions could potentially weaken the muscle on the descending limb of the force-length relationship (Rassier *et al.*, 1999), stressing the importance of ensuring that muscles are trained at all lengths in order to avoid increasing the risk of injury (Proske *et al.*, 2007).

4.6 Conclusion

Overall, elastic resistance elicited similar levels of total and peak activation to weight resistance, suggesting that both methods may be equally effective in producing strength adaptations. However, muscular adaptations at specific phases of ROM differed between conditions because elastic resistance generated lower activation than weights at stretched muscle lengths and higher activation at contracted muscle lengths, where weights generally exhibited a drop in muscular activation. In addition, auxiliary muscles were generally more active under elastic resistance, suggesting that elastic tubes may be more appropriate than weights for proprioceptive training. In conclusion, elastic resistance provoked opposing muscular activation patterns to weight resistance, where as one increased the other decreased, indicating that the two methods may elicit muscular adaptations at differing muscle lengths and could be effectively used as complementary resistance methods.

These results have been observed at $60\text{deg}\cdot\text{s}^{-1}$, which is representative of movement velocities implemented in physiotherapy sessions, it is comparable to previous research and minimises the impact of momentum on muscular activation. However, the results lack ecological validity in that they do not represent training velocities implemented in typical strength training routines. Further studies should therefore address the impact of movement velocity on muscular activation patterns during elastic resistance exercise.

Chapter 5

The effect of movement velocity on muscular activation during weight and elastic resistance exercise

Aspects of this chapter were presented at the "8th Asia-Pacific Conference on Sports Technology" October 15-19th 2017 (Tel Aviv, Israel) and published in the book of abstracts.

5.1 Abstract

INTRODUCTION: The effects of high speed weight resistance exercise on muscular responses are well documented, where an increased electromyographic (EMG) amplitude, a reduced time-to-peak activation and an increased motor unit firing frequency are among the established responses mentioned in the literature. Given the increased popularity of elastic training, and the importance of understanding the mechanisms behind this resistance method, the effects of velocity on muscular activation patterns under elastic and weight resistance were investigated and compared.

METHODS: Moderately active males ($n=22$; age=25±8 years) performed 10 bicep curls and leg extensions with 6kg weights and equivalent load elastic tubes at 60, 120 and $180\text{deg}\cdot\text{s}^{-1}$. Muscular activations of the biceps brachii, triceps brachii, rectus femoris, vastus medialis, vastus lateralis and biceps femoris were recorded with Trigno wireless electrodes (2000Hz) and 3D-motion capture with Qualysis Track Manager (240Hz). Average muscular activation per 20° of range of motion (ROM), peak activation and total activation over 10 repetitions were determined.

RESULTS: In the bicep curl, biceps brachii peak activation was equivalent in both conditions and increased with velocity ($p<.001$), while biceps total activation was higher ($p<.016$) with dumbbells due to an increased activation in the eccentric phase at higher velocities, which was not observed with tubes. Triceps peak activation was higher with tubes ($p=.004$) but was not affected by velocity; while triceps total activation increased with velocity ($p<.001$) in both conditions.

In the leg extension, rectus femoris peak activation increased ($p=.007$) in the elastic condition and remained equal in the weight condition at higher velocities. Total rectus femoris activation remained equal between resistances, but patterns showed increased activation with weight resistance in the eccentric phase at higher velocities ($p<.01$) which was not observed with tubes. Vastus lateralis and medialis total and peak activation were higher ($p<.05$) in the elastic condition at $180\text{deg}\cdot\text{s}^{-1}$. Biceps femoris activation became inappreciable at higher velocities under both resistances.

DISCUSSION: Peak activation occurred at earlier stages of movement at increasing action velocity with weights, while it persisted at the latter stages of ROM with tubes. At higher velocities, weights required greater force to overcome inertia at early stages of ROM, while momentum reduced the required activation at the end of the ROM. Contrastingly, the increasing tension of tubes provoked an equally increasing neural response regardless of movement velocity, producing peak activations at the end of the ROM regardless of velocity.

Tubes and weights may therefore be equally effective in inducing neural and strength adaptations and may be particularly complementary in high velocity training programmes by eliciting higher levels of muscular activation throughout the entire ROM if combined.

5.2 Introduction

Resistance training is seldom uniform in its application in different sporting contexts and with different athletes. One important variable that is sometimes overlooked is the angular velocity at which the individual displaces the resistance and the impact that this has on muscular activation throughout the ROM. The current literature has extensively covered the effects of movement velocity on muscular activation during weight resistance training (Ingebrigsten *et al.*, 2009; Blazevich and Sharp, 2005; Munn *et al.*, 2005, Knight and Kamen, 2001; Aagard *et al.*, 2000; Van Cutsem *et al.*, 1998; Behm, 1991), but little is known about how it affects muscular responses under elastic resistance.

It has been suggested that low training velocities with low weight should be used for injured or untrained individuals to avoid abrupt increases in muscular activation, while high velocities must be included in the advanced stages of strength training programmes to maximise strength gains (ACSM, 2002). In addition, when movements are purposefully performed at low velocities there is a significant reduction in force production (ACSM, 2002), which is reflected in a lower electromyographic activity (van Cutsem *et al.*, 1998) and ultimately in lesser strength gains (Munn *et al.*, 2005).

Increasing movement velocity during weight resistance exercise has been found to increase maximal firing frequency of motor units, hence enhancing force output and rate of force development, ultimately producing neuromuscular adaptations that involved an enhanced maximal torque, a decreased time-to-peak tension and an earlier onset of electromyographic (EMG) activity (Knight & Kamen, 2001; Van Cutsem *et al.*, 1998). Particularly, training at high velocities produces greater strength gains than lower velocities (Munn *et al.*, 2005; ACSM, 2002; Keeler *et al.*, 2001) where angular velocities of 180-240deg·s^{-1} have been found to produce the greatest strength adaptations (Kanehisa and Miyashita, 1983). These findings support the understanding that neural adaptations are responsible for initial increases in strength during high speed training, rather than hypertrophic factors alone (Hakkinen & Komi, 1983), and suggest that by repeatedly recruiting high activations earlier in the ROM with weight resistance, motor units gain the capability to respond faster to central neural stimuli, hence producing faster contractions.

Given that acceleration is inversely proportional to inertia, elastic materials have been speculated to enable greater accelerations at the beginning of the ROM due to their minimal mass (Frost *et al.*, 2010), and would be expected to gradually decelerate the movement as they apply greater load through an increasing stretch at the end of the ROM (Behm, 1991). There is, however, no indication of whether elastic resistance would produce similar muscular responses to weights at high movement velocities. Only one study has examined different velocities of a leg extension under elastic resistance (Matheson *et al.*, 2001) reporting an increase in peak and average EMG in the concentric phase for all muscles, but not in the eccentric phase; overlooking, however, the specificity of muscular activation patterns throughout the ROM. Considering that eliciting muscular activation at different stages of ROM is presumed to effect changes in muscle architecture (Brughelli *et al.*, 2010; Rassier *et al.*, 1999), it is equally important to investigate the effect of velocity on muscular activation patterns under elastic resistance and to what degree they differ from the application of weight resistance at high velocities. The aim of this study was therefore to investigate the effect of movement velocity on muscular activation patterns during elastic and weight resistance exercise.

5.3 Methodology

5.3.1 Participants

Twenty-two moderately active males (age= 25 ± 8 years, stature= 179 ± 7 cm, mass= 76 ± 14 kg) were recruited for the study on a voluntary basis, in accordance with participant specifications described in Section 3.2. All participants signed an informed consent and PAR-Q form before testing (Appendix A). The study was approved by Kingston University Faculty's Ethics committee in line with the declaration of Helsinki.

5.3.2 Conditions

In this study, participants exercised at three different average angular velocities (60 deg·s^{-1}, 120 deg·s^{-1}, 180 deg·s^{-1}) with a Silver Thera-band® tube (T60, T120, T180) and with a 6Kg weight (W60, W120, W180). Having determined from Chapter 4 that T10 (tube with 10% initial stretch) elicited more similar muscular responses to weights than other tube lengths during the bicep curl, the elastic condition in this study was prepared at 10% initial stretch per participant.

5.3.3 Procedures

The study consisted of recording muscular activation throughout the ROM of two exercises: bicep curls and leg extensions, each tested under two types of resistances (Tubes, Weights) at three angular velocities (60 deg·s^{-1}, 120 deg·s^{-1}, 180 deg·s^{-1}).

Before the tests, the participant's skin was thoroughly cleaned and Trigno surface wireless electrodes (DelSys Inc., Boston, USA) were positioned on each muscle in accordance with SENIAM guidance (SENIAM, 2012) (Section 3.4.1). Retroreflective markers were then placed on bony landmarks of exercising limbs for 3D motion capture in order to record joint angles (Section 3.4.2). Participants warmed up with dynamic exercise for 5 minutes, which included jogging and dynamic stretches of the arms and legs. Participants then performed isometric maximal voluntary contractions (MVC) on a Biodex Dynamometer (Biodex Corporation, NY, USA) for all tested muscles (Section 3.4.1).). In a random order, participants then performed a set of ten repetitions for each condition. Three minutes of rest were provided between sets to help avoid the effects of fatigue. Movement velocity was controlled with a video of every exercise performed at constant velocity; the participants were required to practice mirroring the video without resistance prior to the trials to become accustomed to the velocity, the video was then left running throughout testing as a reference for movement velocity.

5.3.4 Data sampling and processing

EMG (mV) was recorded for the biceps brachii, triceps brachii, rectus femoris, vastus lateralis, vastus medialis and biceps femoris with Trigno wireless electrodes at 1926Hz (Section 3.4.1). Participants performed three MVCs for each muscle prior to commencing the trials (Section 3.4.1), which were then used to calculate EMG data as a percentage of their maximal voluntary contraction (%MVC) in order to normalise it between participants. Raw EMG data were averaged by root mean square (RMS) and plotted as activation (%MVC) against joint angle (degrees) through EMGworks Analysis software. Peak EMG was recorded as the mean of three peaks, each taken from the first three repetitions, the middle four, and the final three respectively (Section 3.4.3). Total activation was calculated as the integrated RMS EMG curve over a full set of ten repetitions, where total activation for the elastic conditions was normalised to the weight condition by reporting the former as a ratio of the latter. Muscular activation patterns were drawn by calculating the average EMG for every 20° of ROM from three repetitions of each set. Joint angles were tracked using 3D motion capture through Qualisys Track Manager at 231Hz.

5.3.5 Statistical Analysis

A Shapiro-Wilk test was used to determine normality using the statistics software IBM SPSS 24 (IMB SPSS Inc, Chicago, USA). Effect size (using ETA squared) and observed power were also computed using the software. To determine the effect of movement velocity on muscular activation within one type of resistance (Tubes or Weights), two separate repeated measures ANOVAs were performed among velocities, one per resistance method, with factor one being Movement Velocity (60, 120, 180deg·s^{-1})

and factor two being ROM (7 levels for the bicep curl, 6 for the leg extension). Significance was accepted at alpha = .05 for all statistical tests. Where significant differences were found, LSD *post-hoc* was used to determine significant differences between velocities at specific ROM intervals. Concentric and Eccentric phases were analysed separately.

To determine the differences between resistance methods at each velocity, a repeated measures ANOVA was performed for each velocity, with factor one being Resistance (Tubes, Weights) and factor two being ROM. Where significant differences were found, paired t-tests with Bonferroni correction were used to determine differences at specific ROM intervals. Concentric and Eccentric phases were analysed separately.

Peak and total activation values were analysed through a two-way ANOVA, with factor one being Movement Velocity (60, 120, 180deg$\cdot$s^{-1}) and factor two being Resistance (Tubes, Weights). LSD *post hoc* was used if significant differences were found.

5.5 Results

5.5.1 Bicep Curl

5.5.1.1 Biceps Brachii

During the bicep curl, muscular activation of the biceps was significantly different (p=.047) between resistance methods at all three velocities (Figure 5.1), where weights elicited a significantly higher activation at the beginning of the ROM, and tubes elicited a higher activation at the end of the ROM.

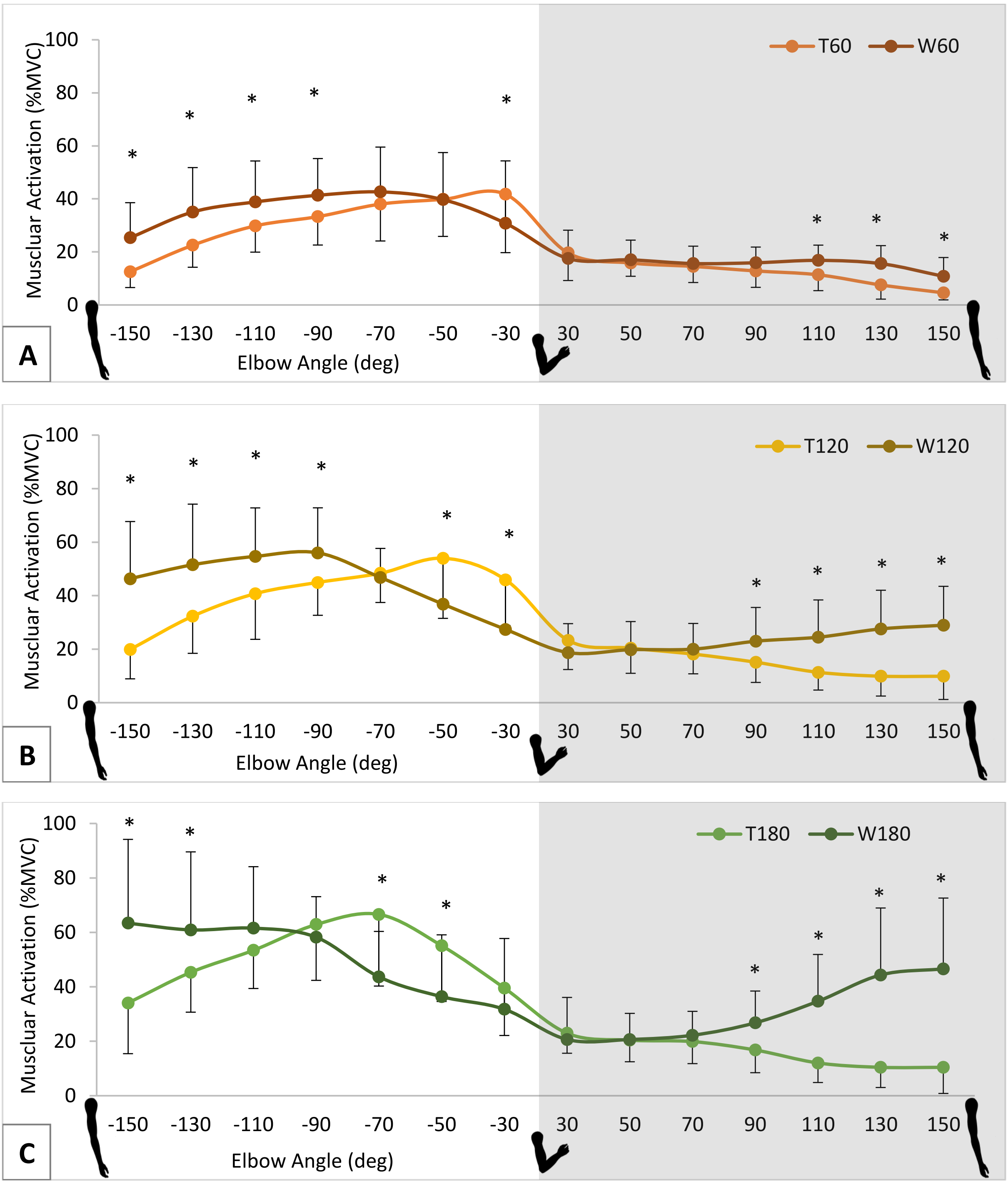


Figure 5.1 - Mean ± SD muscular activation (n=22) of the biceps brachii muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl at movement velocity 60 deg·s^{-1} *(A), 120 deg·s*$^{-1}$ *(B) and 180 deg·s*$^{-1}$ *(C), for two resistance methods (elastic tubes and free weights). *Significant difference between resistance methods (p<.01).*

The occurrence of peak muscular activation was affected by movement velocity in both conditions, appearing at earlier stages of ROM and with greater magnitudes as velocity increased. In the elastic condition, peak activation occurred at 30°, 50° and 70° elbow angle of the concentric phase at 60, 120 and 180deg·s^{-1} respectively; while in the weight condition, peak activation occurred at 70°,90°, and 150° elbow angle (Appendix D, Figure 0.2). Peak biceps activation was also significantly lower (p<.001) at 60 deg·s^{-1} than at other velocities for both resistance methods (Figure 5.2). Despite peak activation occurring at different joint angles, hence causing significant differences between methods throughout the ROM, its magnitude was not significantly different between resistance methods at equivalent velocities (Figure 5.2).

Total muscular activation, calculated as integrated RMS EMG for 10 repetitions, decreased significantly (p<.001) as velocity increased for both resistance methods (Figure 5.3), while total activation for W was significantly higher (p=.004) than T at 120 deg·s^{-1} and 180 deg·s^{-1}.

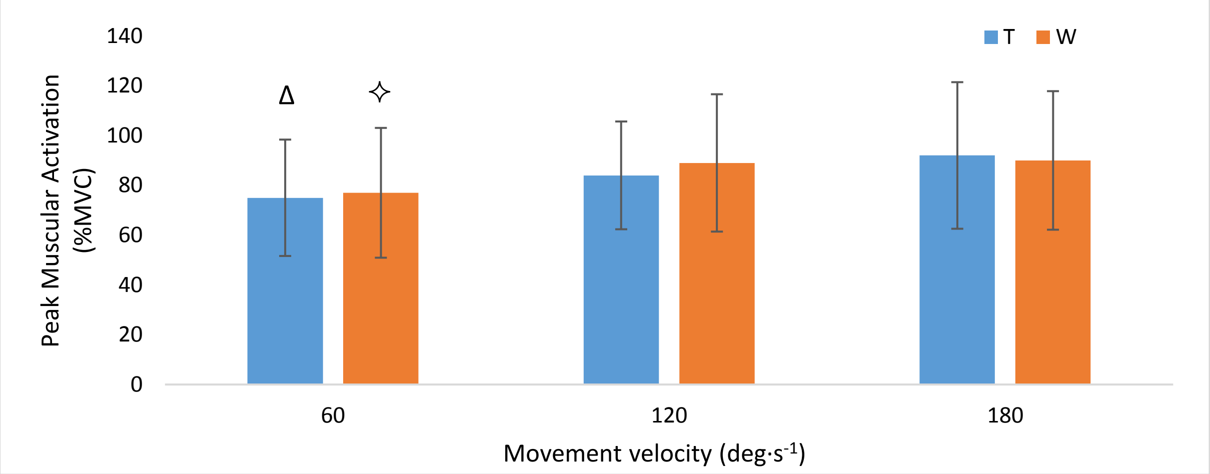


Figure 5.2 - Mean ± SD (n=22) peak muscular activation for the biceps brachii. Δ Peak activation at movement velocity 60deg·s^{-1} significantly lower (p<.001) than all other velocities for tubes; ✧ Peak activation at movement velocity 60deg·s^{-1} significantly lower (p<.001) than all other velocities for weights.

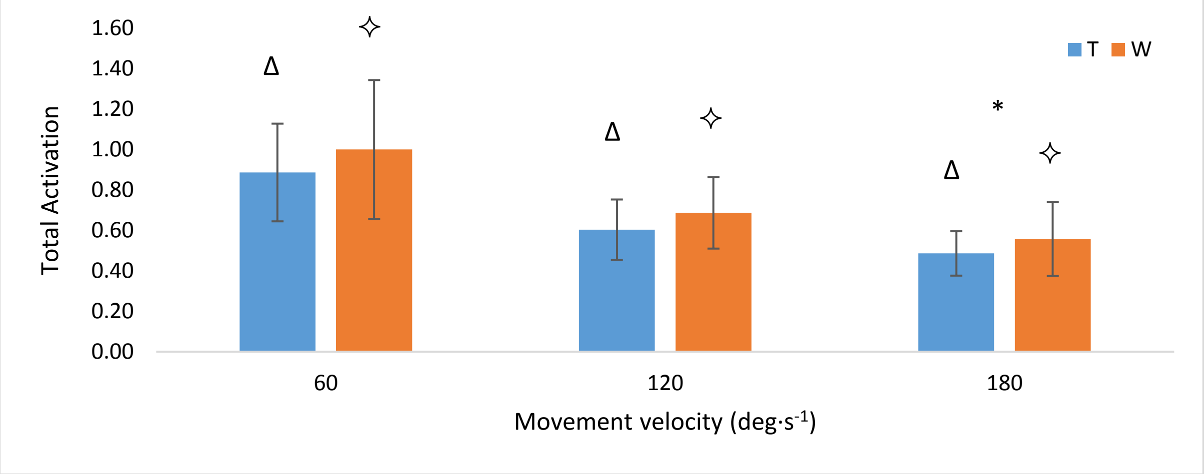


*Figure 5.3 - Mean ± SD (n=22) ratio of total muscular activation for the biceps brachii. Δ Significant difference (p<.001) between all velocities for tubes; ✧ Significant difference (p<.001) between all velocities for weights; * Significant difference between conditions (p<.016).*

5.5.1.2 Triceps Brachii

Muscular activation patterns of the triceps showed similar tendencies to the biceps, where elastic resistance displayed trends of higher triceps activation at the end of the ROM and lower activation than weight resistance at the beginning of the ROM for all velocities (Figure 5.4). Given the high variance of the triceps data, none of these trends were statistically significant, although absolute peak activation was significantly higher (p=.004) in the elastic condition at all velocities (Figure 5.5).

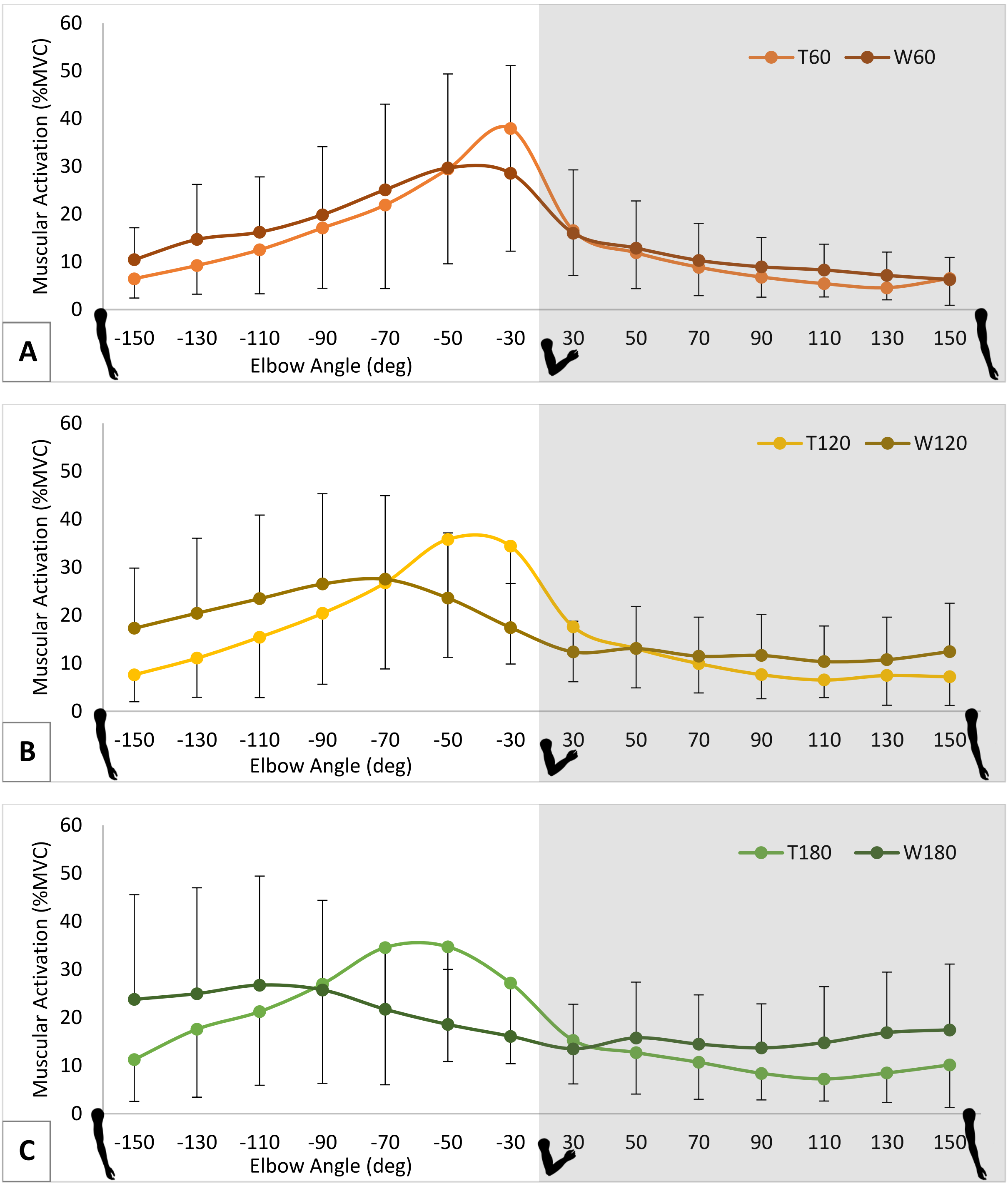


Figure 5.4 - Mean ± SD muscular activation (n=22) of the triceps muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl at movement velocity 180 deg·s^{-1}, for two resistance methods (elastic tubes and free weights).

Similarly to the biceps, peak activation of the triceps occurred at different stages of ROM between conditions: in the elastic condition peak activation occurred at 30°, 50° and 50° elbow angle of the concentric phase at 60,120 and 180deg·s^{-1} respectively, while in the weight condition peak activation occurred at 50°,70°, and 110° elbow angle. Peak activation therefore occurred at smaller elbow angles as velocity increased in both conditions (Appendix D, Figure 0.3).

Peak triceps activation was significantly (p=.004) higher in the elastic condition at all velocities (Figure 5.5). There was no significant change in magnitude of peak activation with movement velocity.

Total muscular activation over ten repetitions decreased significantly (p=.05) as velocity increased, but was not different between conditions.

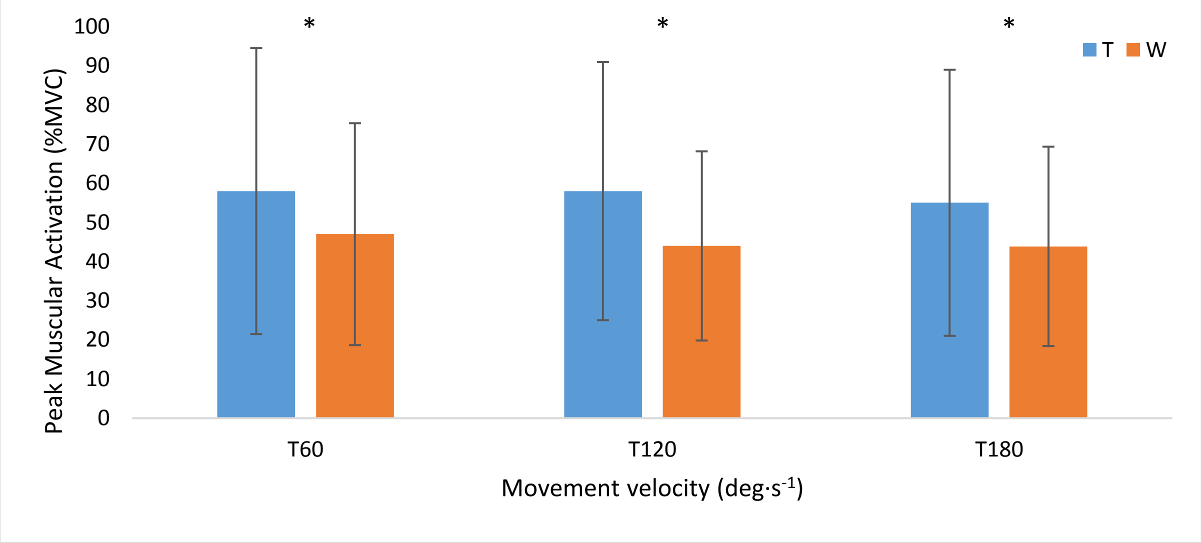


*Figure 5.5 - Mean ± SD (n=22) peak muscular activation for the triceps. * Significant difference (p=.004) between resistance methods at all velocities.*

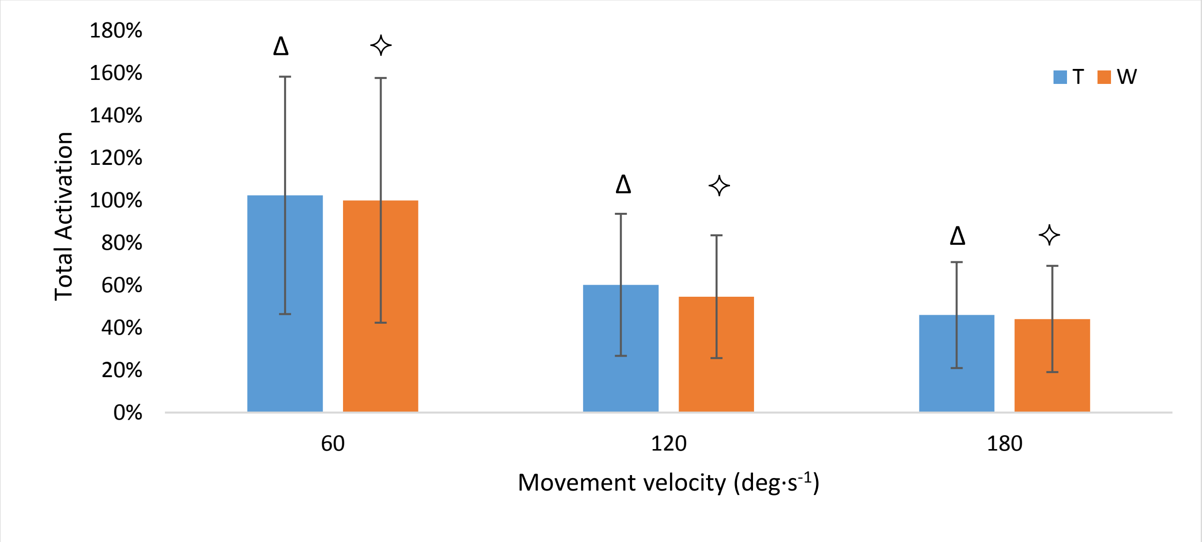


*Figure 5.6 - Mean ± SD (n=22) ratio of total muscular activation for the triceps. *Significant difference between all velocities for both conditions (p=.05).*

5.5.1.3 Angular Velocity

There were no significant differences in angular velocity patterns between conditions at 60 deg·s^{-1} or 120 deg·s^{-1}. At 180 deg·s^{-1} (Figure 5.7) the elastic condition enabled significantly higher accelerations during elbow flexion (p=.02) and decelerations during the elbow extension (p=.019). Several participants exhibited a reduced ROM for W at high velocities; because angular velocity data was not taken from all participants, Figure 5.7C displays no data for W in the first segment of the ROM.

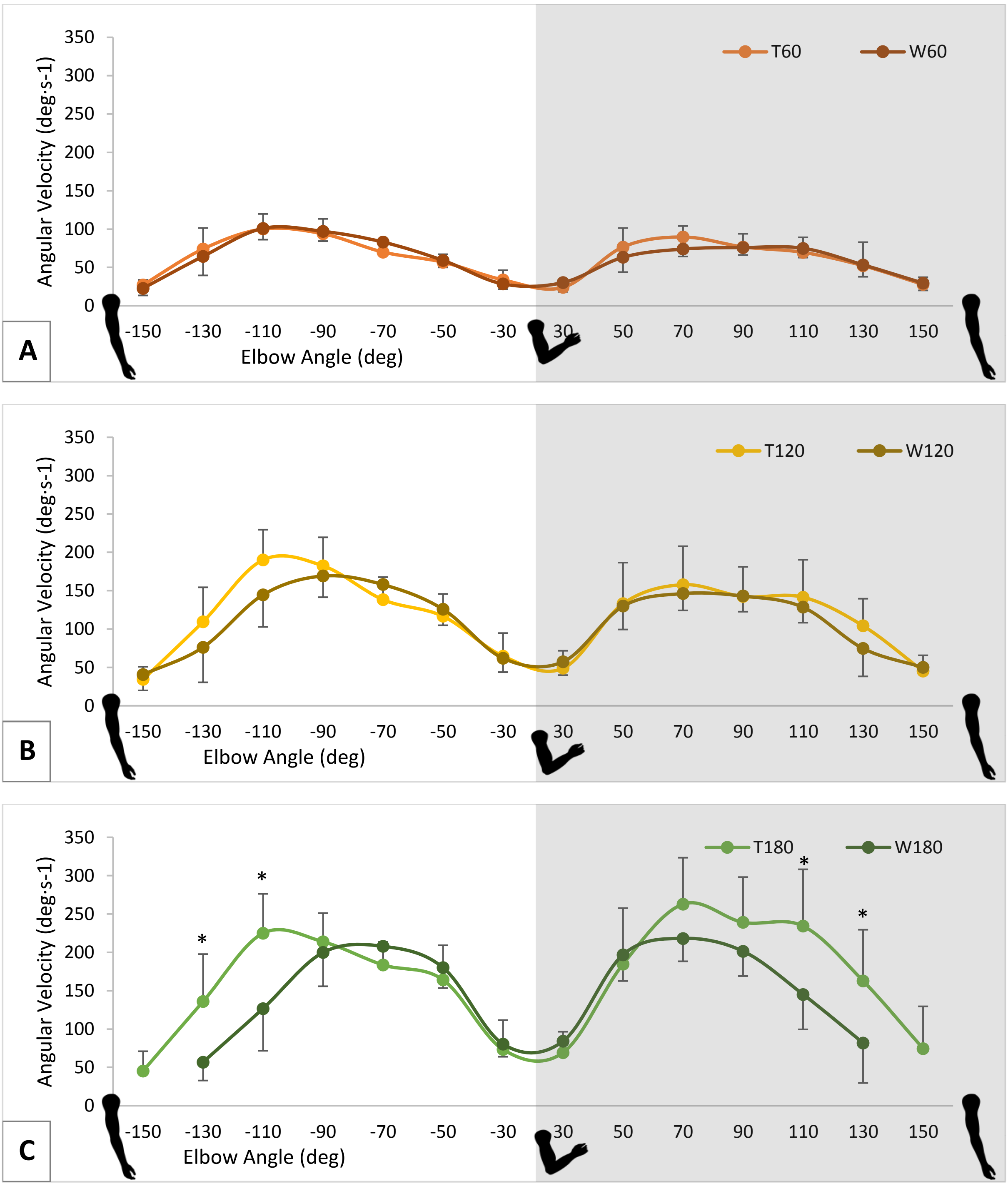


*Figure 5.7 - Mean ± SD measured angular velocity (n=10) of the elbow per every 20° of ROM, throughout the entire range of motion of a bicep curl at movement velocity 60 deg·s^{-1} (A), 120 deg·s^{-1} (B) and 180 deg·s^{-1} (C), for two resistance methods (elastic tubes and free weights). *Significant difference between tubes and weights (p≤.016).*

5.5.2 Leg Extension

5.5.2.1 Rectus femoris

During the leg extension, There were no significant differences in rectus femoris activation between resistance methods at the two lower velocities, 60 deg·s^{-1} (Figure 5.8-A) and 120 deg·s^{-1} (Figure 5.8). At 180 deg·s^{-1} (Figure 5.8-C) weight resistance elicited greater activation than tubes throughout the eccentric phase (p=.012).

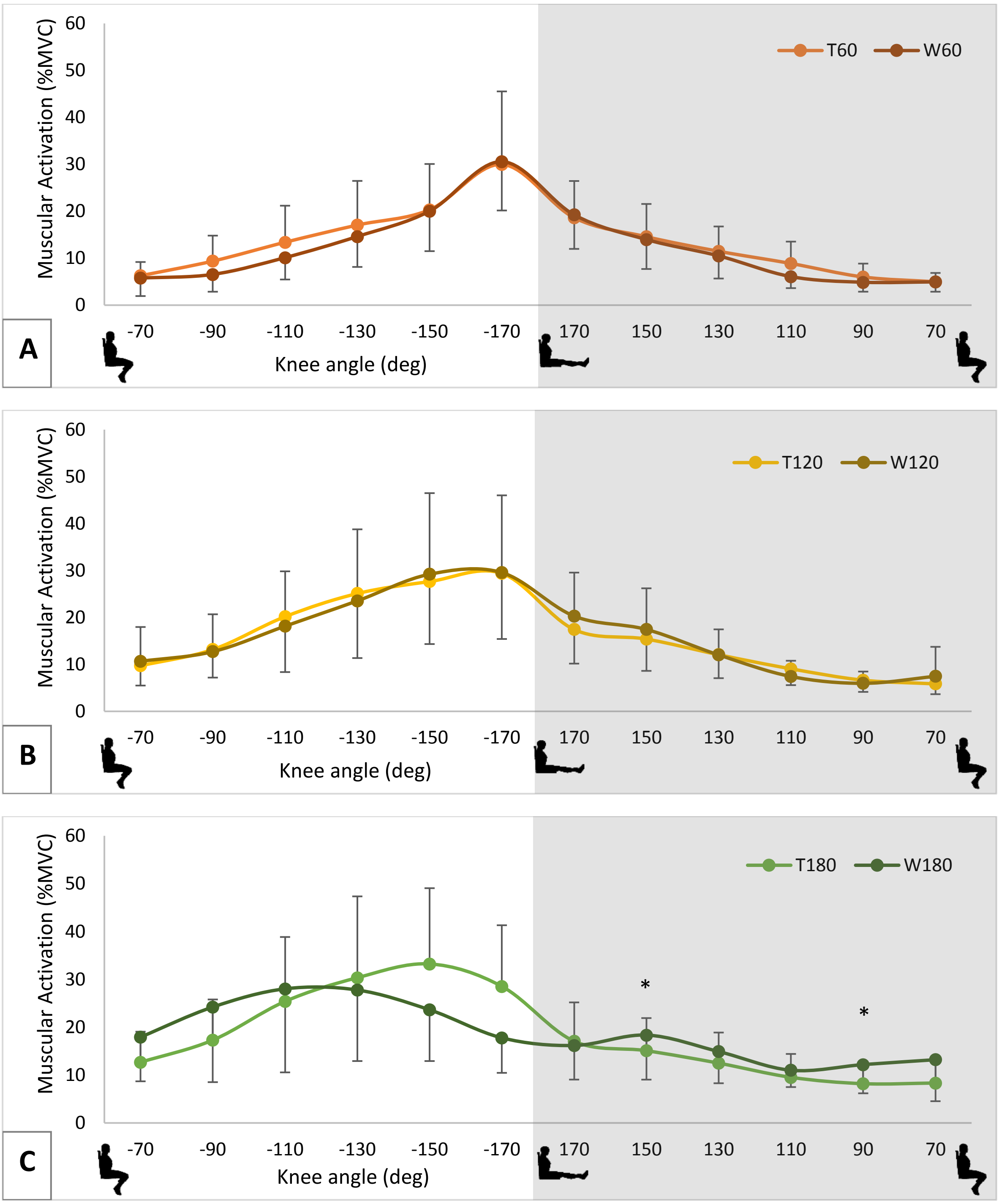


*Figure 5.8 - Mean ± SD muscular activation (n=22) of the Rectus Femoris muscle per every 20° of ROM, throughout the entire range of motion of a leg extension at movement velocity 60 deg·s^{-1} (A), 120 deg·s^{-1} (B) and 180 deg·s^{-1} (C), for two resistance methods (elastic tubes and free weights). *Significant difference between resistance methods (p<.01)*

Overall activation of the rectus femoris significantly increased (p<.001) with movement velocity in the concentric phase under both elastic and weight resistance (Appendix D, Figure 0.5 & Figure 0.6). Eccentric activation of the rectus femoris also increased significantly (p<.001) with velocity in the weight condition, but was not affected under elastic resistance (Appendix D, Figure 0.5 & Figure 0.6).

Peak activation occurred earlier in the ROM at 180°s^{-1} for both resistance methods (Figure 5.8), while absolute peak activation increased with velocity (p=.007) for the elastic condition only (Figure 5.9). Total activation (Figure 5.10) did not differ between resistance methods, but significantly decreased (p<.001) with movement velocity in both.

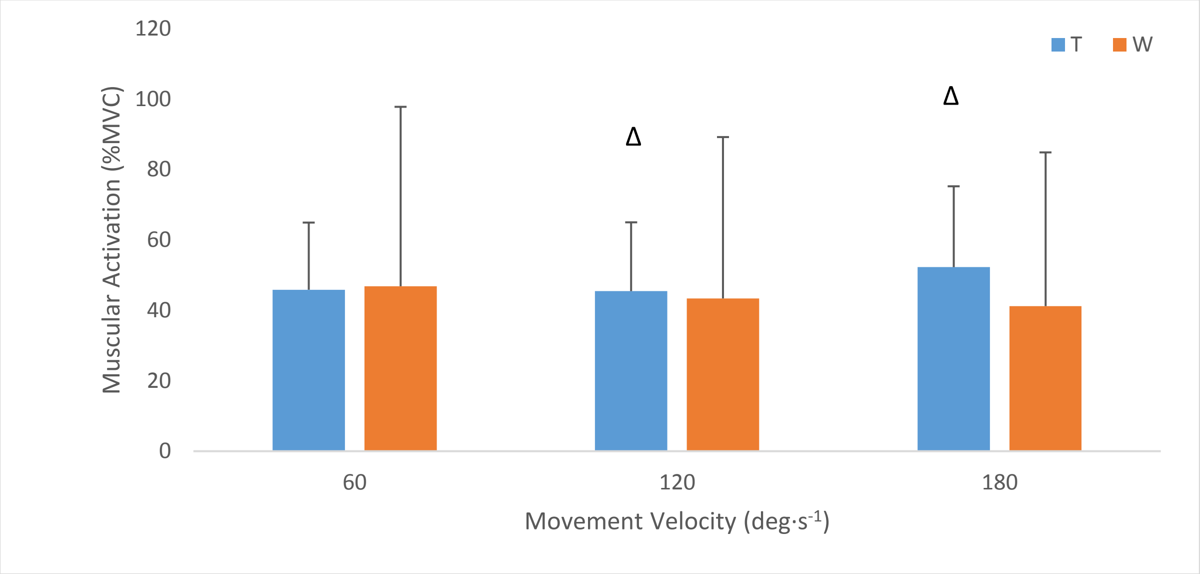


Figure 5.9 - Mean ± SD (n=22) peak muscular activation for the Rectus Femoris when performing a Leg Extension at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}), under two resistance methods (T,W). Δ Significant difference (p=.007) between T120 and T180.

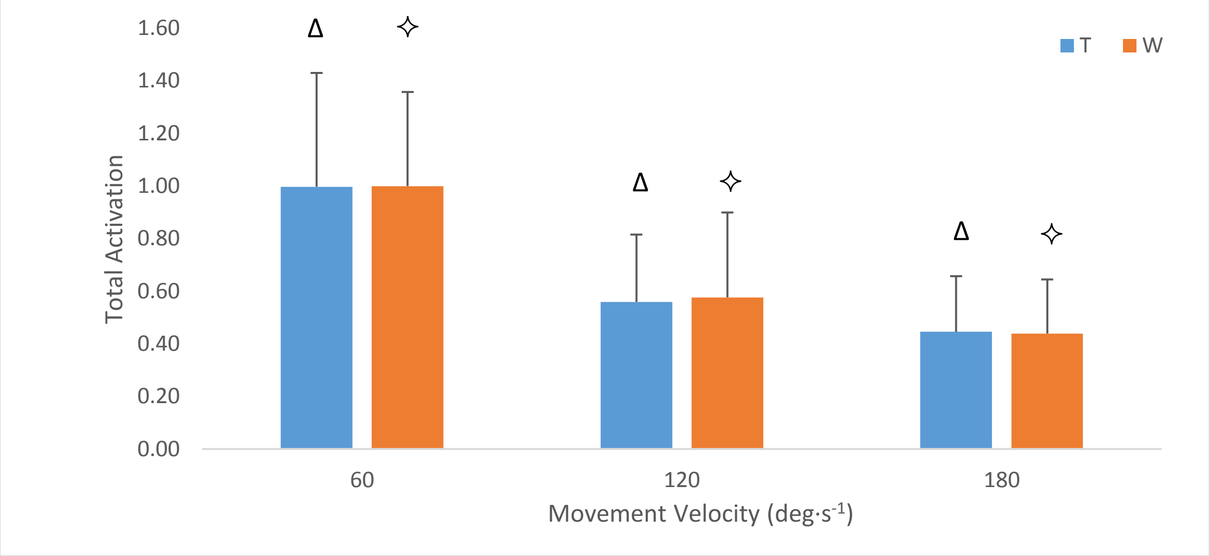


Figure 5.10 - Mean ± SD (n=22) ratio of total muscular activation for the Rectus Femoris when performing a Leg Extension at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}), under two resistance methods (T,W). Δ Significant difference (p<.001) between all velocities for tubes; ✧ Significant difference (p<.001) between all velocities for weights.

5.5.2.2 *Vastus Medialis*

Activation of the vastus medialis was significantly higher in the elastic condition at all three velocities in both the concentric (p=.012; p<.001; p=.001) and eccentric (p<.001; p=.002; p=.003) phases (Figure 5.11).

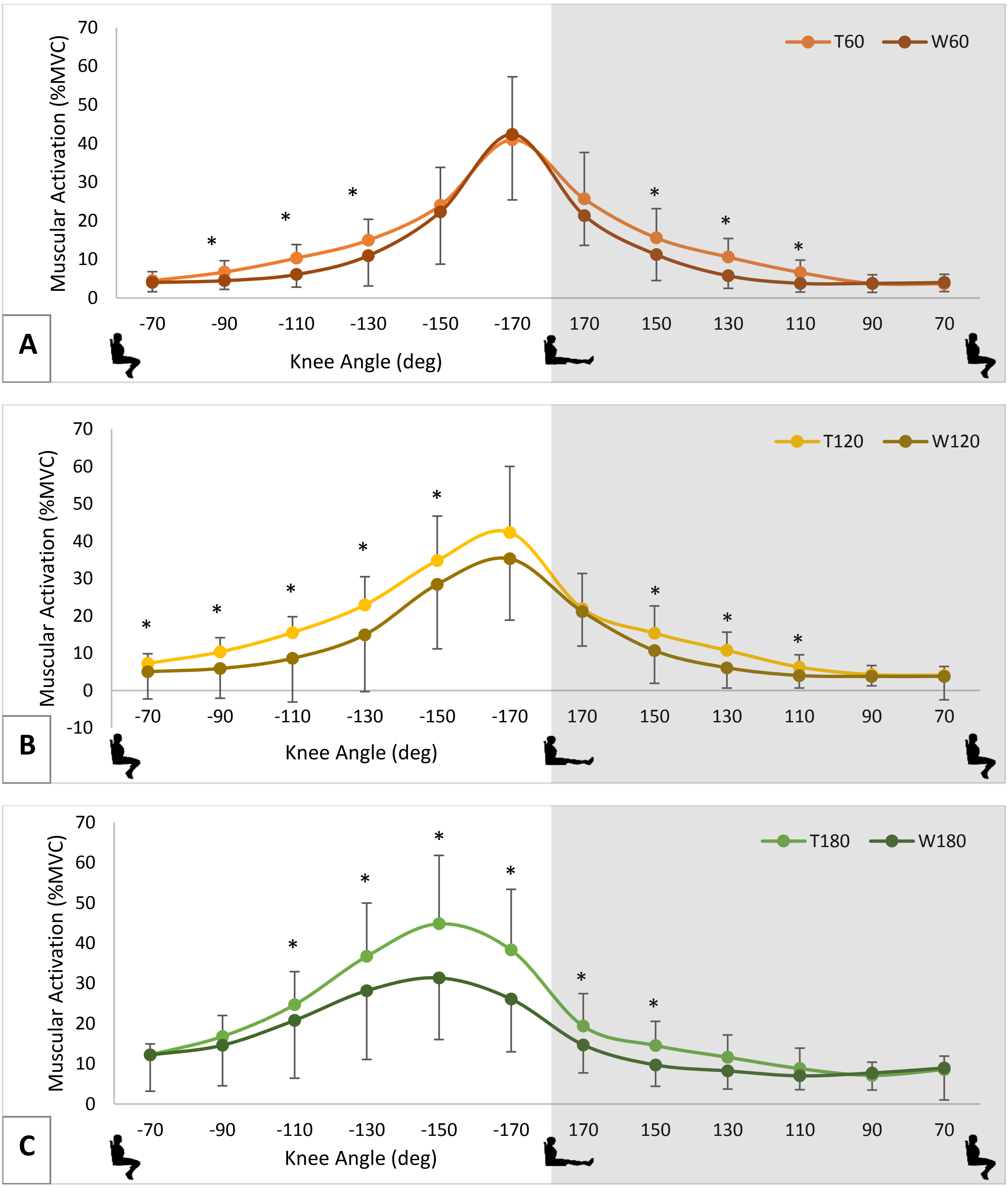


*Figure 5.11 - Mean ± SD muscular activation (n=22) of the Vastus Medalis per every 20° of ROM, throughout the entire range of motion of a leg extension at movement velocity 60 deg·s^{-1} (A), 120 deg·s^{-1} (B) and 180 deg·s^{-1} (C), for two resistance methods (elastic tubes and free weights). *Significant difference between resistance methods (p<.01).*

Muscular activation of the vastus medialis significantly increased ($p \leq .001$) with movement velocity throughout the concentric phase with both elastic and weight resistance (Appendix D, Figure 0.7 & Figure 0.7).

Peak activation occurred 20° earlier in the ROM at 180deg·s^{-1} for both resistance methods. Absolute peak activation of the vastus medialis (Figure 5.12) decreased significantly ($p=0.44$) with movement velocity in the weight condition, while it significantly increased ($p=.044$) with velocity from 120deg·s^{-1} to 180deg·s^{-1} in the elastic condition. Elastic resistance elicited a significantly higher ($p=.005$) peak activation than weights at 180deg·s^{-1}. Total muscular activation (Figure 5.13) significantly decreased ($p<.001$) from 60deg·s^{-1} to 120deg·s^{-1} for both resistance methods, and was significantly higher ($p=.017$) under elastic resistance at all three velocities.

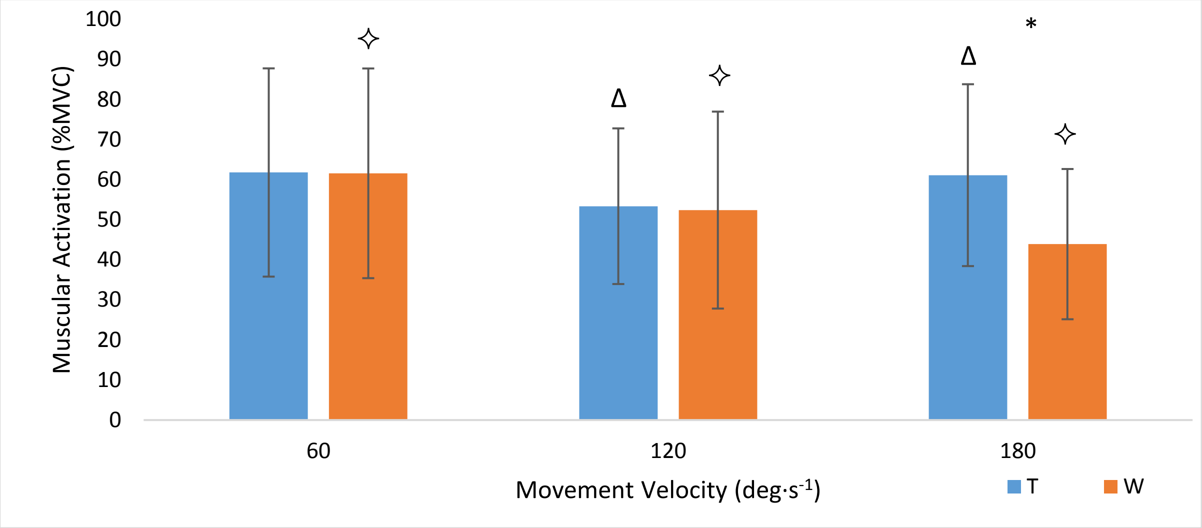


*Figure 5.12 - Mean ± SD (n=22) peak muscular activation for the Vastus Medialis when performing a Leg Extension at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}), under two resistance methods (T,W). * Significant difference ($p=.005$) between resistance methods at 180deg·s^{-1} Δ Significant difference ($p=.044$) between T120 and T180; ✧ Significant difference ($p=.044$) between W60,W120,W180.*

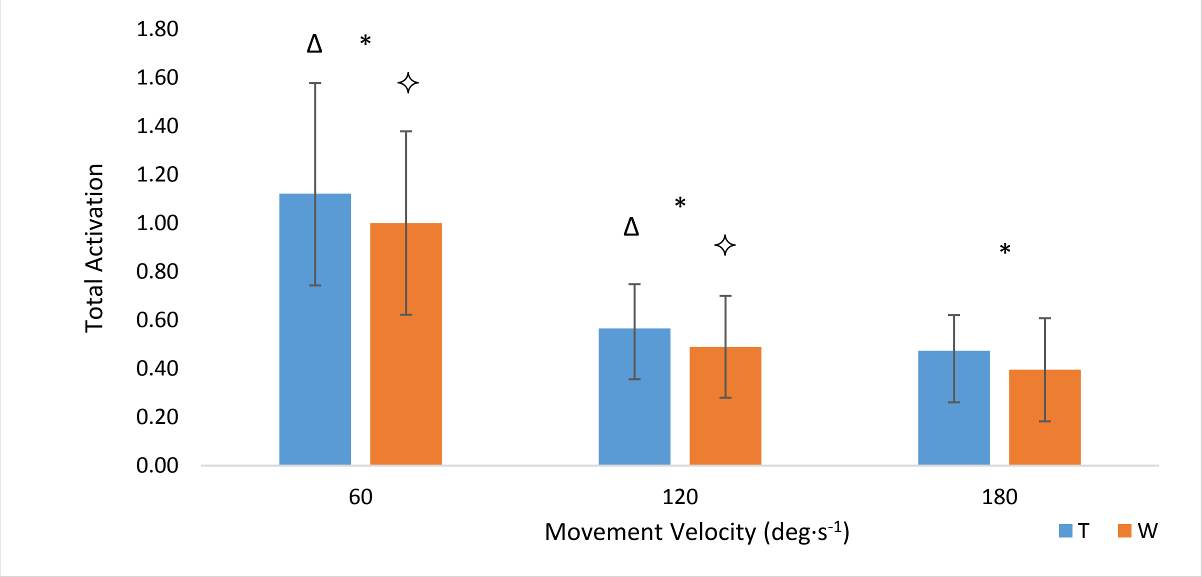


*Figure 5.13 - Mean ± SD (n=22) ratio of total muscular activation for the Vastus Medialis when performing a Leg Extension at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}), under two resistance methods (T,W). Δ Significant difference ($p<.001$) between T60 and T120; ✧ Significant difference between W60 and W120; * Significant difference ($p=.017$) between resistance methods.*

5.5.2.3 *Vastus Lateralis*

Activation of the vastus lateralis was significantly higher in the elastic condition at all three velocities in both the concentric (p=.003; p=.001; p<.001) and eccentric (p<.001; p=.001; p=.003) phases (Figure 5.14).

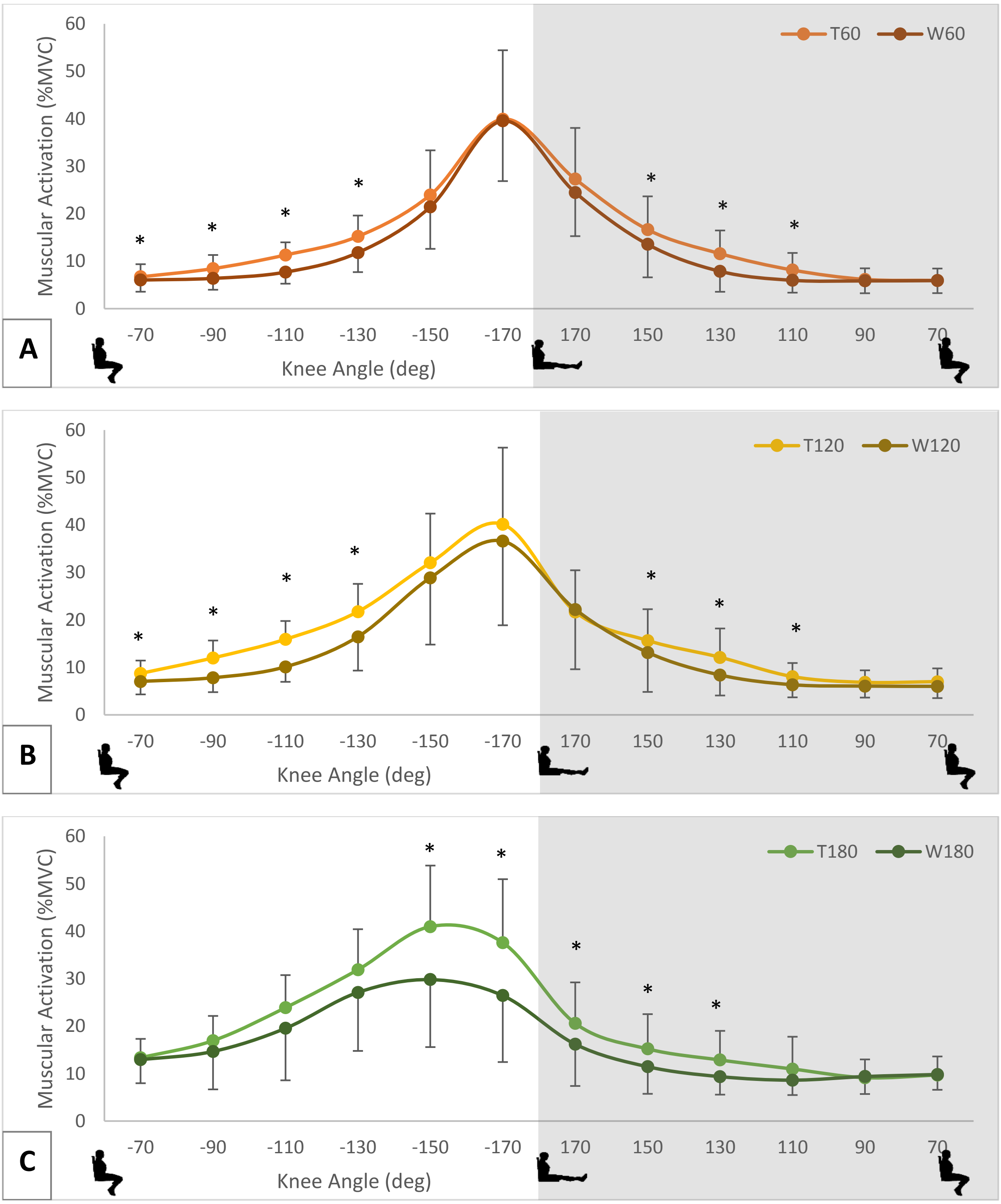


*Figure 5.14 - Mean ± SD muscular activation (n=22) of the Vastus Lateralis per every 20° of ROM, throughout the entire range of motion of a leg extension at movement velocity 60 deg·s^{-1} (A), 120 deg·s^{-1} (B) and 180 deg·s^{-1} (C), for two resistance methods (elastic tubes and free weights). *Significant difference between resistance methods (p<.01).*

Muscular activation of the vastus lateralis significantly increased (p≤.001) with movement velocity throughout the concentric phase within both the elastic and weight resistance (Appendix D, Figure 0.9 & Figure 0.10).

Peak activation of the vastus lateralis occurred 20° earlier in the ROM at 180deg·s^{-1} under both resistance methods. Absolute peak activation (Figure 5.15) also significantly decreased (p<.001) with movement velocity in the weight condition, and was significantly lower (p=.016) than the elastic condition at 180deg·s^{-1}. Total muscular activation (Figure 5.16) decreased significantly (p<.001) with velocity, and was higher under elastic resistance at all velocities, reaching statistical significance (p=.010) only at 180deg·s^{-1}.

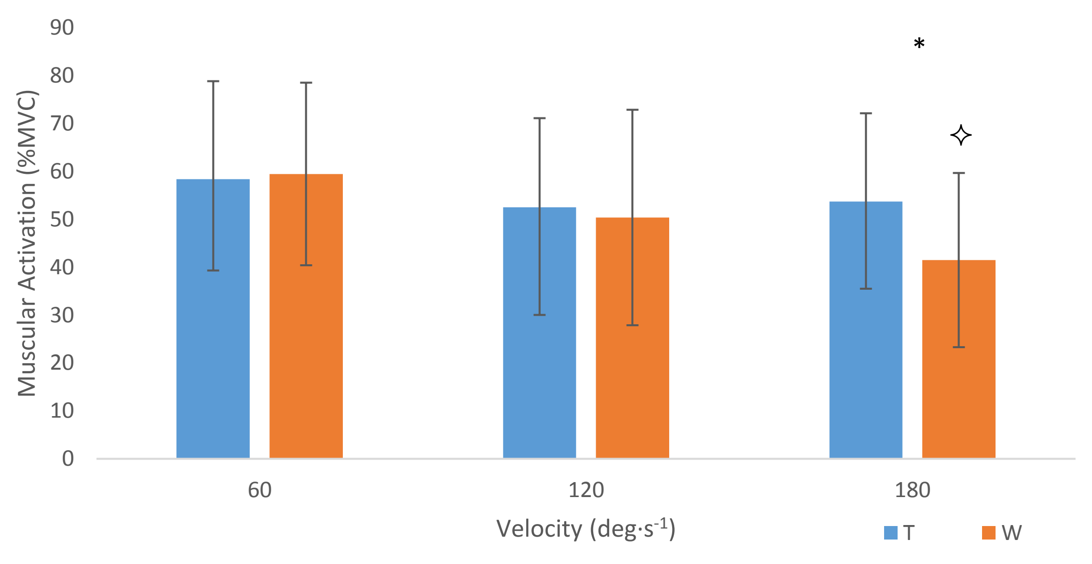


*Figure 5.15 - Mean ± SD (n=22) peak muscular activation for the Vastus Lateralis. *Significant difference (p<.01) between resistance methods at 180deg·s^{-}; ✧ W180 is significantly lower (p<.05) than W60 and W120.*

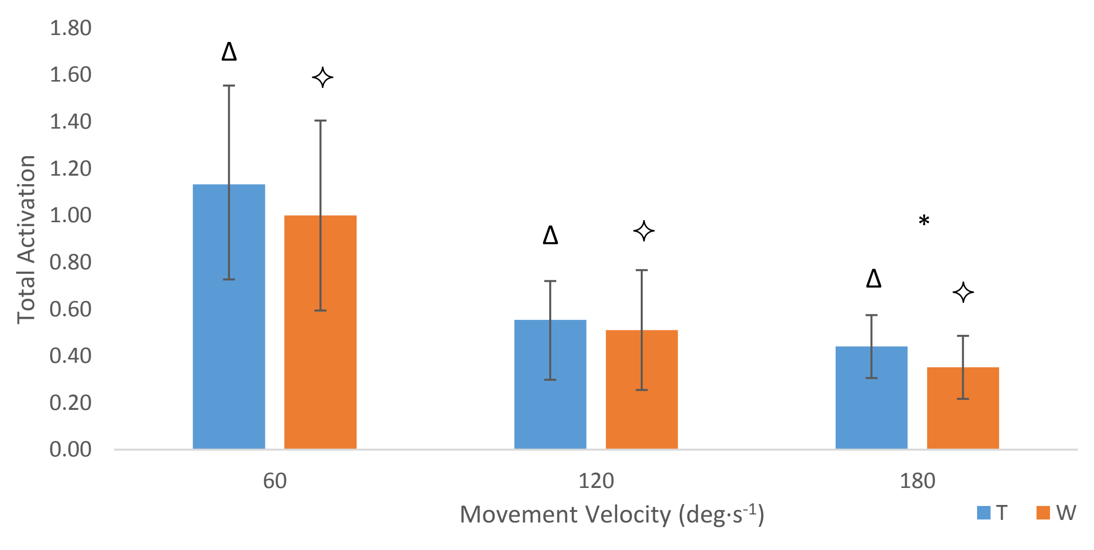


*Figure 5.16 - Mean ± SD (n=22) ratio of total muscular activation for the Vastus Lateralis. * Significant difference (p=.010) between resistance methods at 180deg·s^{-}; ✧ Significant difference (p<.001) between velocities for weights; Δ Significant difference (p<.001) between velocities for tubes.*

5.5.2.4 Biceps Femoris

Weight resistance elicited a significantly higher activation of the biceps femoris than elastic resistance at 60deg·s^{-1} (Figure 5.17-A) during both the concentric ($p<.001$) and eccentric ($p=.003$) phases. There were no differences between conditions at 120deg·s^{-1} and 180deg·s^{-1}.

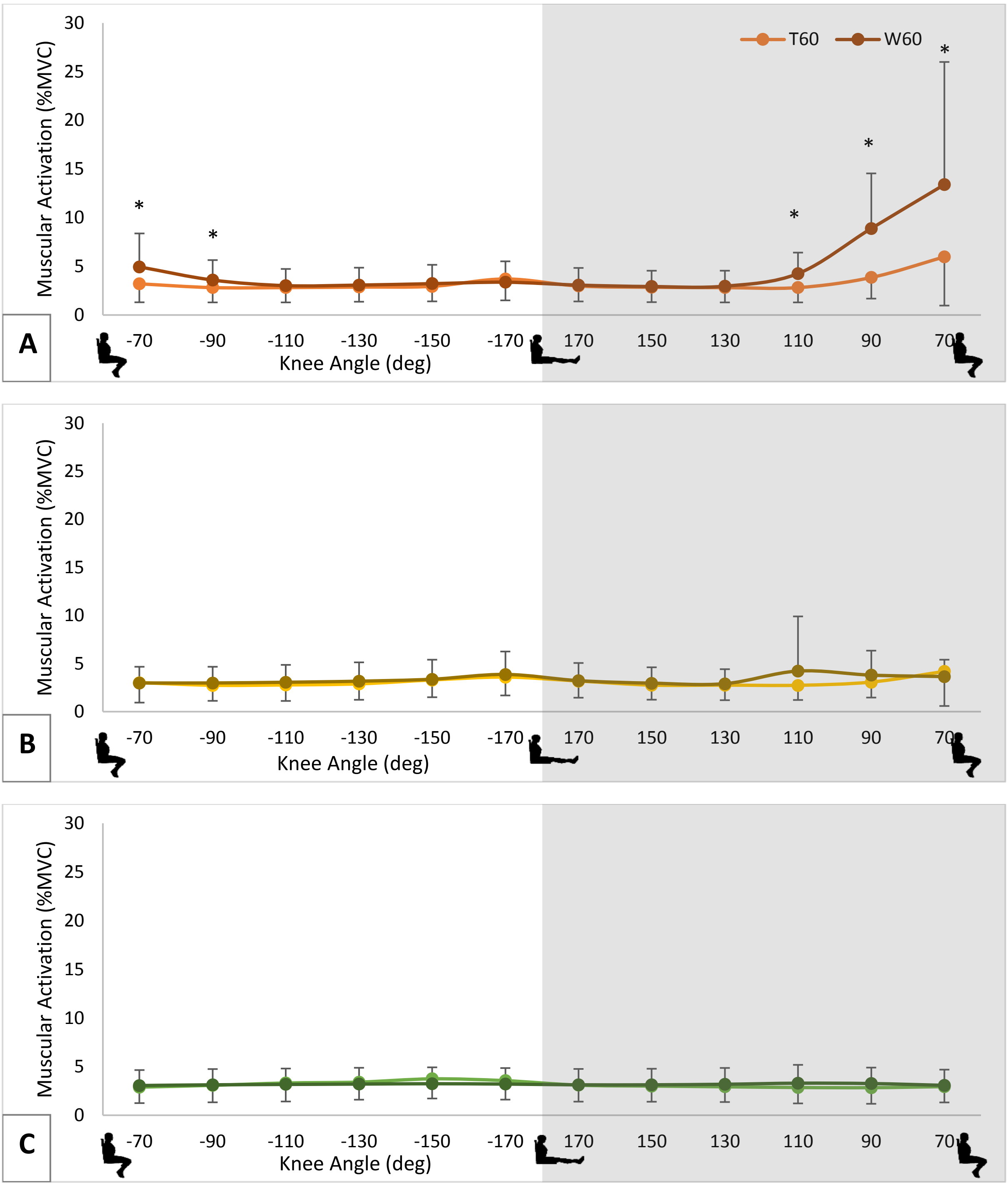


Figure 5.17 - Mean ± SD muscular activation (n=22) of the Biceps Femoris per every 20° of ROM, throughout the entire range of motion of a leg extension at movement velocity 60 deg·s^{-1} (A), 120 deg·s^{-1} (B) and 180 deg·s^{-1} (C), for two resistance methods (elastic tubes and free weights).

Absolute peak activation (Figure 5.18) was higher ($p<.001$) at 60deg·s^{-1} than all other movement velocities for both resistance methods, and was higher ($p=.025$) with weight resistance with respect to elastic resistance at that same velocity. Similarly, total activation (Figure 5.19) was higher ($p<.001$) at 60deg·s^{-1} than at all other velocities for both resistance methods, where it was also higher ($p=.001$) with weight resistance.

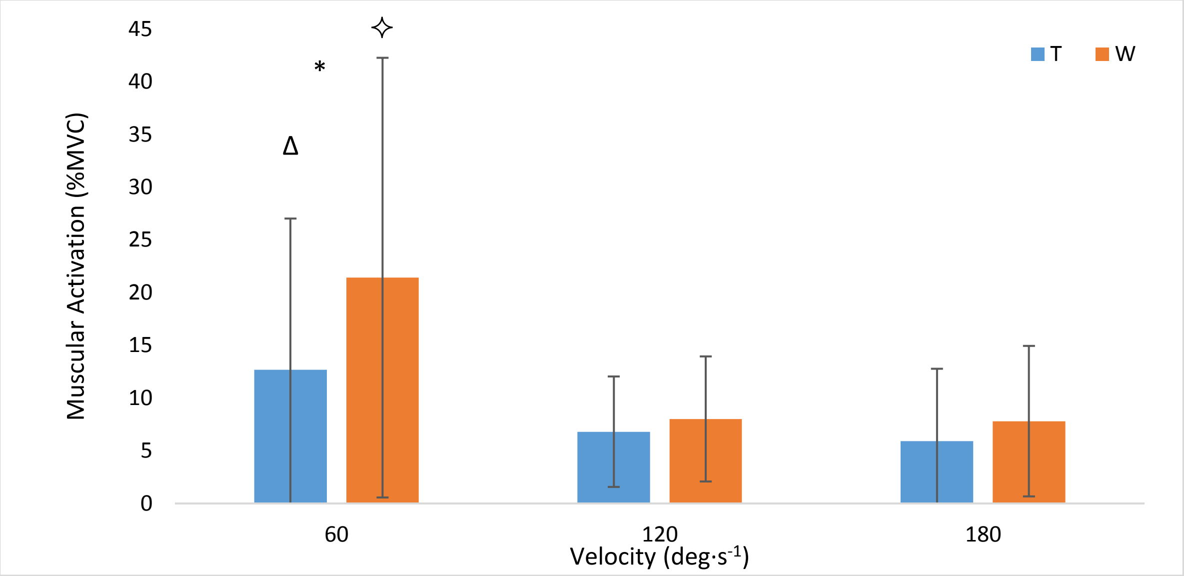


*Figure 5.18 - Mean ± SD (n=22) peak muscular activation for the Biceps Femoris. * Significant difference ($p<.01$) between resistance methods at 60deg·s^{-1}; ✧ Peak activation at 60deg·s^{-1}significantly higher ($p<.001$) than at other velocities for weights; Δ Peak activation at 60deg·s^{-1}significantly higher ($p<.001$) than at other velocities for weights.*

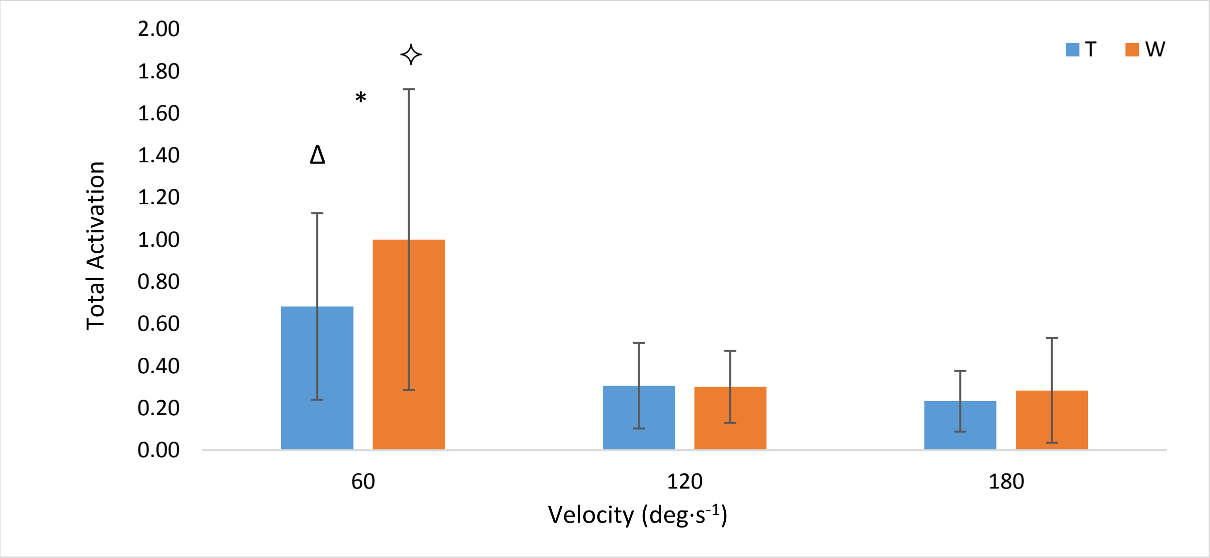


*Figure 5.19 - Mean ± SD (n=22) ratio of total muscular activation for the Biceps Femoris. ◊ Significant difference ($p=.001$) between resistance methods at 60deg·s^{-1}; * total activation at 60deg·s^{-1}significantly higher ($p<.001$) than at other velocities for both methods. ✧ Peak activation at 60deg·s^{-1}significantly higher ($p<.001$) than at other velocities for weights; Δ Peak activation at 60deg·s^{-1}significantly higher ($p<.001$) than at other velocities for weights.*

5.5.2.5 Angular Velocity

There were no statistical differences in angular velocity between resistances, where 60deg·s^{-1} and 120deg·s^{-1} exhibited nearly identical patterns in angular velocity throughout the ROM, and 180deg·s^{-1} showed trends of higher accelerations at the beginning of the ROM in the elastic condition with respect to the weight condition (Figure 5.20).

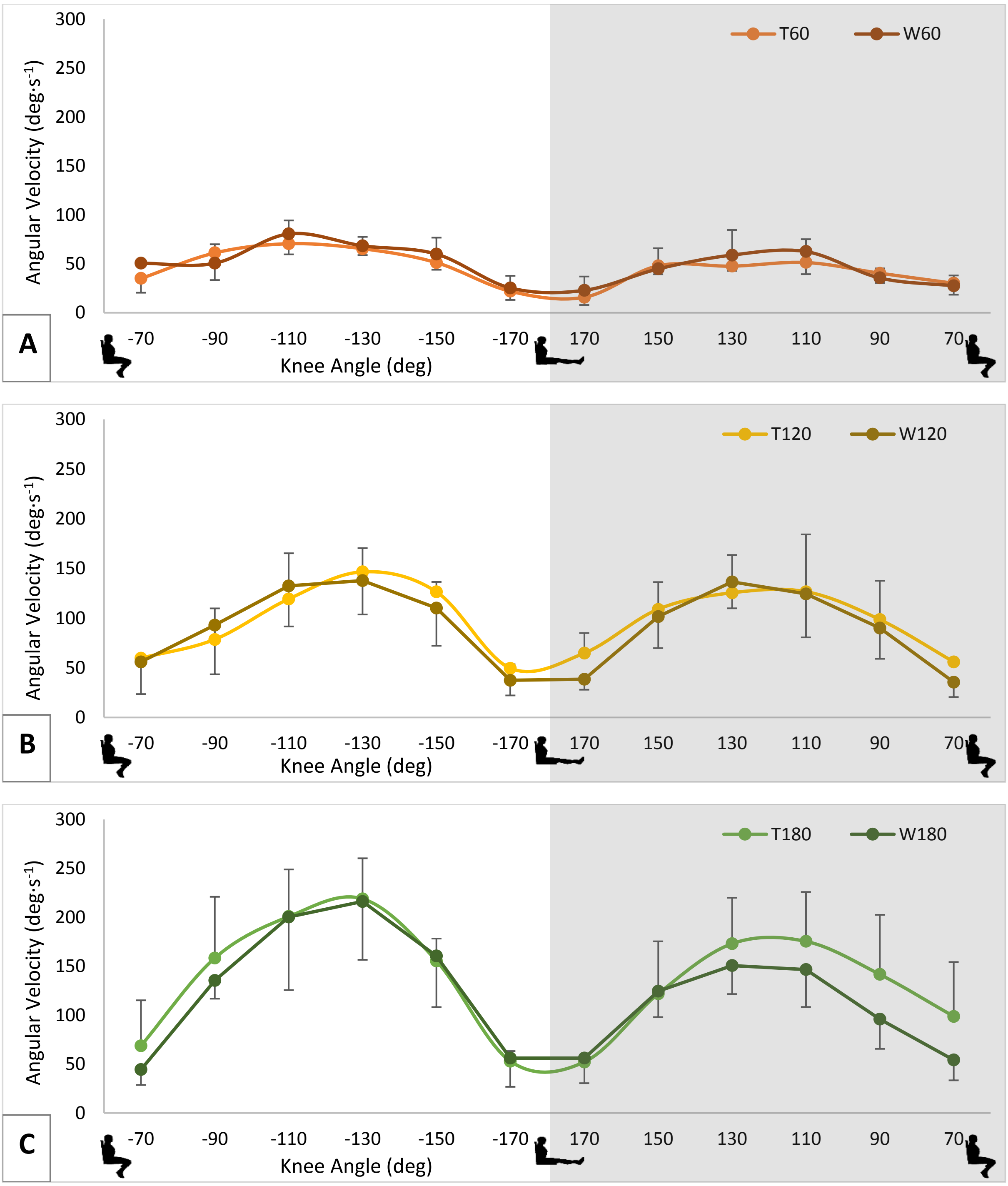


Figure 5.20 - Mean ± SD measured angular velocity (n=10) of the knee per every 20° of ROM, throughout the entire range of motion of a leg extension at movement velocity 60 deg·s^{-1} (A), 120 deg·s^{-1} (B) and 180 deg·s^{-1} (C), for two resistance methods (elastic tubes and free weights).

5.6 Discussion

The main findings of this study indicate that the differences in muscular activation patterns previously observed in Chapter 4 become more pronounced at higher movement velocities, where peak muscular activation shifted towards earlier stages of movement as velocity increased, occurring at longer muscle lengths with weight resistance and remaining at shorter muscle lengths under elastic resistance. The shift in peak activation to earlier stages of the ROM is consistent with literature on high speed weight training (Sakamoto & Sinclair, 2012) and can be attributed to two interdependent factors: one neurological and the other mechanical.

5.6.1 Neuromuscular factors

Neurologically, high speed weight training has been found to exhibit an earlier onset of EMG activity with respect to moderate and slow velocities (Sakamoto & Sinclair, 2012), with a marked reduction in time-to-peak EMG activation (van Cutsem *et al.*, 1998) as observed in this study. Faster movement velocities require a higher initial force output in anticipation of the increased effort, implementing a greater motor unit recruitment earlier in the concentric phase, which would explain the higher EMG readings in those stages of movement. Moreover, given that fast twitch fibres produce faster responses and a higher rate of force development than slow twitch fibres (Fry, 2004), faster movements are more likely to recruit the former. Type IIa and IIb muscle fibres are typically composed of type IIa and IIb myosin heavy chains (MHC) respectively, which are capable of faster power strokes during the cross bridge cycle than type I MHC (Fry, 2000); this action requires a greater myosin ATPase activity (Gur *et al.*, 2003; Barany, 1967), enabling greater rates of depolarization and repolarization, which produce higher, and shorter, action potentials (Kupa *et al.*, 1995). Fast twitch muscle fibres are in fact innervated by fast-fatiguing motoneurons with large cell bodies (Dum and Kennedy, 1980), which enable a higher axon conduction velocity and firing rate (Gardiner, 1993), causing the motor units to exhibit high recruitment thresholds and therefore produce higher EMG readings (Cormie *et al.*, 2011). Finally, adaptive increases in motor unit firing frequency and time-to-peak activation have been observed concomitantly with increases in maximal force output and rate of force development following high speed training (Cormie *et al.*, 2011; van Cutsem *et al.*, 1998; Cracraft *et al.*, 1997), indicating that neural adaptations are, at least in part, responsible for muscular adaptations. Given that, in this study, agonist time-to-peak activation was reduced significantly more in the weight condition than in the elastic condition in both exercises, high speed training might be more effective at producing neural adaptations with weight rather than elastic resistance. The reduced time-to-peak activation observed in the weight condition can induce adaptations in motor unit recruitment and rate of force development, which would improve power and speed performance (Cormie *et al.*, 2011; van Cutsem *et al.*, 1998; Cracraft *et al.*, 1997). The outcome would, however, would be much less prominent and less likely with elastic training due to the delayed onset on peak activation that this method produces.

5.6.2 Biomechanical factors

Mechanically, the inertia presented by the weight requires sufficient muscular force to be moved from its starting position. At higher velocities, the high initial activation of the muscle produced a high moment of inertia, which brought the limb through the ROM, reducing the need for muscle action in its latter stages. In line with the findings presented in this chapter, previous studies have observed that high speed training with low isotonic resistance produces strong accelerations at initial stages of movement, coupled with a high agonist activation, and a deceleration towards the end of the ROM that is also concurrent with a reduction in agonist activation (Sakamoto & Sinclair, 2012; 2006).

Under elastic resistance however, the mechanical influence of load differed substantially from the weight condition. While the weights' mass required a significant initial counter force to overcome inertia, at initial stages of movement the elastic tension was lower and required less force (Table 4.1). In fact, as speculated by Frost *et al.* (2010), when training at higher velocities (T180), the tubes facilitated the production of faster velocities earlier in the ROM with respect to weights due to their imperceptible mass and to their low resistance at early stages of movement (Figure 5.7; Figure 5.20).

As the limb then progressed throughout the ROM, elastic tension increased, requiring muscular activation to also rise, hence the occurrence of peak activation later in the ROM.

Given that the resistance of elastomers increases at higher strain rates (Young and Lovell, 1991), it can be speculated that the increased rate of elongation at high velocities may have directly influenced the increases in muscular response at the end of the ROM. However, in a study on material properties of Thera-Band® tubing, Patterson *et al.* (2001) found no effect of strain rate on elastic load of the materials, ruling out this possibility.

In the weight condition, the enhanced eccentric activity of the agonist muscles at final stages of the bicep curl and leg extension was affected by a need to counteract the load's momentum in decelerating the limb and changing direction for the next repetition. One might also argue that, due to the electromechanical delay between EMG readings and force production, reportedly to ranging between 10ms – 100ms (Buchanan *et al.*, 2005), the higher activation at the end of the eccentric phase might simply be a projection of the increased activation at the beginning of the following repetition. The increase in eccentric activation, however, is observed 640 ms before the beginning of the next repetition, therefore ruling out this possibility. Contrastingly, this phenomenon was not observed in the elastic condition due to the decreasing tension that the tubes generate as they shorten. In addition, the higher angular velocities observed in the extension phase of the elastic condition also indicate that the low eccentric activation can be attributed to the tubes' recoil force, which aided the extension of the elbow joint.

Therefore, considering that at high velocities total biceps activation was greater for weight resistance due to a greater eccentric activation, and that during dynamic exercises eccentric muscle action contributes to strength adaptations as much as the concentric action does (Roig *et al.*, 2008), it is conceivable that high-speed training may produce greater overall strength gains for weight resistance rather than for elastic resistance. However, given the increased activation at the end of the concentric phase under elastic resistance, and the lack thereof in the weight condition at high velocities, combining the two resistances should generate muscular activation throughout the entire movement, producing enhanced strength adaptations across all sections of the ROM. When devising training programmes, the main limitation to high speed and ballistic training with weights is the lack of overload at the end of the ROM (Behm *et al.*, 1991). The findings contained in this chapter may therefore be particularly useful to power lifters and for sport-specific training that requires muscular overload throughout the entire ROM of fast or powerful movements, where combining an elastic tension to weighted loads could provide the additional exertion at the end of the ROM. On the other hand, the fact that elastic resistance still maintains its gradual application of force even at high velocities also reinforces the notion that it may be more appropriate than weights in rehabilitation settings. Recovering patients may benefit from the neurological adaptations that are provided by high speed training by being able to exercise at high velocities with a gradual increase in load.

In summary, at higher velocities, a high initial agonist activation in the weight condition produced an angular momentum that aided the weight through the full ROM, requiring less activation at the end of the concentric phase; while in the elastic condition, the low initial resistance enabled the production of faster velocities at lower efforts, where the arm's angular momentum was gradually overcome by the increasing resistance of the tubes, effecting a higher agonist activation at the end of the ROM in both exercises.

5.6.3 The influence of movement control

In a study on elastic resistance, Aboodarda *et al.*, (2013) reported a bell-shaped activation curve of the biceps muscle during a bicep curl at a cadence of 2 seconds per phase (flexion/extension), while this investigation reports a peak in muscular activation at the end of the ROM at a similar average velocity (60deg·s^{-1}). Having seen the effect of movement velocity on the occurrence of peak activation, the findings in this chapter suggest that the differences in muscular activation patterns from those found Aboodarda *et al.* (2013) may lie in the choice of movement control adopted by the two studies. In a study on movement strategies under elastic resistance, Hodges and Kriellaars (2013) suggested that cadence may not be an effective method of velocity control as it enables variable accelerations between pacing stops, resulting in variations of muscle load throughout the ROM. Based on those findings, this project attempted to maintain movement velocity as constant as possible throughout the entire ROM by requiring the participants to mirror a video during testing (Section 3.3.1.1). It is also worth noting that pilot testing for this study demonstrated a rather wide variance in self-paced velocities, which averaged 105 deg·s^{-1} for both the bicep curl and leg extension (Section 3.3.1.2). This further supports the reflection that during Aboodarda *et al.*'s (2013) study, participants may have been accelerating to velocities higher than 60deg·s^{-1} throughout the ROM due to lack of pace control, producing an earlier occurrence of peak activation. Considering that in real life settings movement control is not present, the findings presented by Aboodarda *et al.* (2013), and by the conditions training at 120 deg·s^{-1} and 180 deg·s^{-1} in this chapter, are more applicable to training programmes than the muscular responses observed at 60 deg·s^{-1}.

5.6.4 Antagonist muscle responses at increased velocities

The effect of velocity on antagonist muscle activation differed between exercises due to differences in set-up. During the bicep curl, triceps peak activation, which was consistently higher under elastic resistance, also occurred earlier in the ROM at higher velocities in synchronisation with peak biceps activation, substantiating previous suggestions that the recoil force of the elastic tubes required greater joint movement control, effecting an agonist-antagonist co-activation (Section 4.5.4). These observations suggest that the joint destabilisation produced by elastic resistance persists at high movement velocities and may increase overall muscular recruitment during high speed training programmes.

During the leg extension, muscular activation of the biceps femoris became imperceptible at higher velocities under both resistances (Figure 5.17). When exercising at 60deg·s^{-1} the biceps femoris exhibited concentric action at knee angles smaller than 90° in order to flex the leg, with a higher activation with weight resistance due to the need to counteract the weight's mass. At higher velocities however, the angular momentum gained during knee flexion swung the leg through the ROM, eliminating the need for hamstring action. These observations underline the importance of considering ROM, momentum and inertial forces when prescribing exercises, as the biomechanics of a movement, and the velocity of its execution, will highly affect patterns in both muscular activation and muscle recruitment.

5.6.5 Synergist muscle responses during the leg extension

During the leg extension, all knee extensors exhibited a shift in peak activation towards early phases of movement at higher velocities, although there were some differences between agonist (rectus femoris) and synergist muscle (vastus medialis and lateralis) reactions to velocity.

The increased peak synergist activation under elastic resistance suggest that there was a greater demand for their stabilizing action at higher velocities. By counteracting the joint moment throughout the ROM, elastic resistance appeared to maintain its destabilizing action, while with weight resistance synergist muscles became less active at high velocities, indicating that elastic resistance remains a more effective method for proprioceptive training than weight resistance, particularly at high velocities.

In addition, peak synergist activation was observed at the same knee angles as agonist activation with elastic resistance, while with weight resistance it occurred 40° later in the ROM with respect to the rectus femoris, suggesting a disruption in agonist-synergist coordination with weight resistance. It has been speculated that power training induces improved coordination of agonist-synergist co-activation (Behm, 1995) and, although the literature does not present sufficient evidence to support this suggestion (Cormie *et al.*, 2011), if correct, it may explain the difference between agonist and synergist peak occurrence at different velocities in the weight condition. It is possible that with weight resistance peaks were not synchronised at higher velocities due to the lack of power training in the participating population. The fact that elastic resistance did not require an earlier activation of synergist muscles, due to lower tension at initial stages of ROM, suggests that weight resistance may be more appropriate at improving agonist-synergist coactivation and rate of force development (Cormie *et al.*, 2011; van Cutsem *et al.*, 1998).

In summary, elastic resistance may be more effective at enhancing muscle recruitment for proprioceptive training, particularly at high velocities, while weight resistance may be more effective at improving rate of force development and agonist-synergist coactivation due to an enhanced muscular activation earlier in the ROM.

5.6.6 Effects of higher movement velocities on architectural adaptations

Chapter 4 discussed the adaptive changes of sarcomere lengths to long term resistance training, where training at long muscle lengths effects an increase of in-series sarcomeres, while the opposite is true for exerting muscles at shorter lengths (Brughellli *et al.*, 2010; Rassier *et al.*, 1999). While it has been extensively suggested that muscles with a greater number of in-series sarcomeres are stronger on the descending limb of the length-tension relationship (Timmins *et al.*, 2016), studies have also mentioned an impact on shortening velocity, where fibres with more in-series sarcomeres can shorten at faster rates given the reduced length of each contractile unit (Cormie *et al.*, 2011; Blazevich & Sharp, 2005; Wickiewicz *et al.*, 1984). Sprint runners have in fact been observed to have longer fascicles than distance runners (Abe *et al.*, 2000), where fibre length further affected sprint performance among athletes (Kumagai *et al.*, 2000). Although high speed training has been associated with increases in fibre lengths (Blazevich *et al.*, 2003), it is still not clear whether high speed training plays a determining role in effecting an increase of in-line sarcomeres, or whether differing morphologies are solely related to genetic factors and architectural adaptations to resistance training at differing muscle lengths.

Given that, at high velocities, agonist muscular activation occurs increasingly earlier in the ROM (at longer muscle lengths) with weight resistance, it could be suggested that high speed training does contribute to adaptations in fibre lengths, not necessarily because of the speed of recruitment, but rather because of the shift in peak activation that fast contractions cause. By causing the muscle to activate earlier in the ROM, high speed training effectively exerts the muscle at longer lengths with weight resistance, hence possibly contributing to architectural adaptations in sarcomeric structure. Moreover, it has been established that the architectural determinants of speed are not associated with muscle fibre type, where both type I and type II fibres typically exhibit sarcomeres of approximately 2.1 µm in length (Hilber and Galler, 1997; Bukholder *et al.*, 1994). Therefore, in addition to enhancing type II fibre twitch response by reducing time-to-peak activation in high speed training, the consequential lengthening of the muscle fibres could produce a global improvement in mechanical shortening velocity, encompassing all muscle fibre types.

COnsdiering that, due to their elastic properties, tubes apply the highest load at the end of the ROM regardless of velocity, they may not provide sufficient overload at initial stages of movement to increase the rate of force development (Frost *et al.*, 2010), and may still not be as effective as weights at producing an increase of in-series sarcomeres as a part of long term adaptations. Although it could be speculated that by substantially reducing the initial length of the tubes they may produce sufficient resistance to provoke the required overload, it must also be noted that elastic resistance increases exponentially with stretch (Santos *et al.*, 2014), possibly impeding finalisation of the movement in such cases.

Therefore, findings in this study indicate that, aside from producing adaptations of the neuromuscular system and recruiting different types of muscle fibres, training at high velocities shifts muscular exertion to different stages of the ROM, possibly affecting long term architectural adaptations of the muscle fibres and sarcomere lengths.

5.6.7 Conclusion

The opposing muscular activation patterns of elastic and weight resistance exercise that are observed at low velocities are enhanced at higher velocities due to inertial effects on the joint moment. At high movement velocities, elastic resistance maintained its increased application of load at the end of the ROM, while weight resistance exhibited a significant shift in peak activation towards even earlier stages of the ROM and a substantial drop in activation at the end of the ROM. These findings reinforce the notion that, while the separate application of elastic and weight resistance are appropriate for proprioceptive and power training respectively, a combination of the two methods may be particularly beneficial in maintaining muscle activation throughout the entire ROM at high velocities.

The findings reported in this study have consolidated that elastic and weight resistance exhibit opposing patterns in muscular activation throughout the concentric phase, and that these differences are enhances at higher movement velocities. The complementary nature of these patterns leads to the suggestion that a combination of the two resistance methods may exert muscular activation throughout the entire ROM, ensuring strength adaptations at all muscle lengths, although this possibility has not yet been explored through EMG analysis. An investigation of the effects of combining the two resistance methods may therefore shed light on these speculations.

Chapter 6

Combining weights and tubes as a method of resistance

6.1 Abstract

INTRODUCTION: Elastic resistance has been found to elicit greater muscular activation at latter stages of movement, where weight resistance often does not provide sufficient muscular overload. Many authors have suggested combining elastic and weight resistances in order to exert the muscle throughout the entire range of motion (ROM), although very few have investigated this option. This study aims to illustrate of the effects of combining elastic and weight resistance on muscular activation patterns during bicep curls and leg extensions.

METHODS: Moderately active males (n=21; age=25±8) performed 10 bicep curls and leg extensions with 6kg weights (W120), an equivalent (Silver Thera-band® tubes) elastic resistance (T120) and a combined condition (TW120) of half elastic tension (Blue Thera-band® tubes) and half weight resistance (2.8kg), at an average angular velocity of $120 deg \cdot s^{-1}$. Muscular activation of the biceps, triceps, rectus femoris, vastus medialis, vastus lateralis and biceps femoris was recorded with Trigno wireless electrodes (1926Hz), joint angles were recorded through 3D-motion capture with Qualysis Track Manager (231Hz). Average muscular activation per every 20° of ROM, peak activation and total activation over 10 repetitions were recorded.

RESULTS: Total activation was equivalent under all conditions for all muscles except the for the biceps during the bicep curl, which was highest ($p<.001$) with weights due to an increased ($p\leq.007$) activation in the eccentric phase not observed under other conditions.

Agonist muscles exhibited equivalent peak activations under all conditions for both exercises, and a muscular activation pattern under TW120 that averaged those of T120 and W120. During the bicep curl, biceps activation was highly active over a larger portion of the ROM under TW120 (110°-70° elbow angle), while W120 and T120 elicited peak activations at mid (90°) and late (50°) stages of ROM respectively and low activations at all other stages.

The synergist muscles of the leg extension (vastus medialis and lateralis) and the antagonist muscle of the bicep curl (triceps) exhibited activation patterns under TW120 that closely reflected those of T120, while W120 was least active ($p<.05$) during the concentric phase of all muscles.

DISCUSSION: The available literature reports equal total muscular activation with weight and combined resistance, but significantly higher strength improvements under combined resistance after 3 or more weeks of training. The findings reported in this study mostly confirm that total activation remains equivalent to weight resistance when substituting a portion of the load with elastic tension, and suggests that the strength improvements observed in the intervention studies were related to an increased time under tension of the agonist muscle with a concomitant increased activation of auxiliary muscles.

In conclusion, combining weight and elastic resistance elicited greater time under tension, producing muscular activation patterns of the agonist muscle that averaged those of weights or tubes on their own, also providing the additional benefit of an increased recruitment of auxiliary muscles.

6.2 Introduction

Elastic resistance has thus far been determined to elicit greater muscular activation at latter stages of movement compared to weight training. Building on this evidence, it has been suggested that a combination of weight and elastic resistance may provide a synergistic effect (Frost *et al.*, 2010; Behm, 1991), eliciting higher levels of muscular activation throughout the entire range of motion (ROM), although very few authors have investigated this option.

Initially, Ebben and Jensen (2002) investigated the effects of substituting 10% of weight load during a back squat with elastic resistance, compared to using only weights (barbell + weight plates). The authors found no differences in integrated electromyography (EMG) or ground reaction forces between the resistance methods and argued that there would be no additional benefits to combining the methods for strength training. However, in a later intervention study on back squats and bench presses, Anderson *et al.* (2008) found that seven weeks of training with a resistance provided by 80% weight load and 20% elastic tension produced significantly greater improvements in 1 repetition maximum (1RM) than weight training alone. Finally, in a similar study, Bellar *et al.* (2011) reported that, after three weeks of bench press training, a combination of 85% weight load and 15% elastic load also provided significantly greater strength gains than weight load alone. The apparently conflicting findings reported by the electromyographic study (Ebben and Jensen, 2002) and the two intervention studies (Bellar *et al.*, 2011; Anderson *et al.*, 2008) therefore reinforce the importance of considering muscular activation patterns, joint specificity and muscle recruitment patterns when comparing different resistance methods.

It was theorised that the greater improvements in the combined condition were due to an increased elastic tension at joint angles that are generally more advantageous with weight resistance (Bellar *et al.*, 2003), where Anderson *et al.* (2008) also hypothesized an alteration in muscle recruitment patterns due to the addition of elastic resistance, which could not be observed in the data provided by Ebben and Jensen (2002) who only reported total activation. The authors' speculations were later supported by analytical research on elastic resistance (Jakobsen *et al.*, 2014; Aboodarda *et al.*, 2013) and by the findings reported in Chapters 4 and 5 of this project, where increased muscular activation was always observed at latter stages of movement in the elastic condition, regardless of angular velocity.

The current literature, however, lacks analytical studies on the specific patterns in loading and muscular activation generated by combining the two resistance methods. In order to gain appropriate understanding for designing effective training programmes, it is important to consider the impact of substituting a portion of weight load with elastic tension on muscular activation patterns. Although the mentioned studies used a small proportion of elastic load in their investigations (10-20%), for the purposes of this study, the loads have been split equally with 50% weight and 50% elastic resistance, hypothesising that loads would therefore be distributed equally throughout the ROM, potentially providing the benefits of both methods. This study, therefore, aims to provide an illustration of muscular activation patterns elicited by combining elastic and weight resistance, at an angular velocity that reflects the average self-determined velocity used during strength training.

6.3 Methodology

6.3.1 Participants

Twenty-one moderately active males (age= 25 ± 8 years, stature= 179 ± 7 cm, mass= 77 ± 13 kg) were recruited for the study on a voluntary basis. All participants signed an informed consent and PAR-Q form prior to commencing testing (Appendix A). The study was approved by Kingston University Faculty's Ethic committee in line with the declaration of Helsinki.

6.3.2 Conditions

Having determined that an angular velocity of $120\text{deg}\cdot\text{s}^{-1}$ was closest to the average self-determined exercising pace (Section 3.3.1.2), and that a 10% reduction in initial tube length was found most appropriate for comparing tubes and weights at equivalent loads (Section 5.3), all conditions in this study were performed at an average angular velocity of $120\text{deg}\cdot\text{s}^{-1}$ and all tubes used were reduced by 10% in initial length. The three conditions differed by resistance type, where one condition consisted in Silver Thera-band® tubes (T120), the second consisted in 6kg weights (W120) and the third was a combined condition (TW120) where the applied load was produced by 47% weight and 53% elastic resistance: using a 2.8Kg weight and a blue Thera-Band® tube (equivalent to 3.2kg at 100% stretch).

6.3.3 Procedures

The study consisted of recording muscular activation throughout the ROM of two exercises: bicep curls and leg extensions, each tested under three types of resistances (Tubes, Weights and Tubes+Weights) at an average angular velocity of $120\text{deg}\cdot\text{s}^{-1}$.

Before testing, the participant's skin was thoroughly cleaned and Trigno surface wireless electrodes (DelSys Inc., Boston, USA) were positioned on each muscle in accordance with SENIAM guidance (SENIAM, 2012) (Section 3.4.1). Retroreflective markers were then placed on bony landmarks of the exercising limbs for 3D motion capture in order to record joint angles (Section 3.4.2). Participants warmed up with dynamic exercise for 5 minutes, which included jogging and dynamic stretches of the arms and legs. Participants then performed unilateral isometric maximal voluntary contractions (MVC) on a Biodex Dynamometer (Biodex Corporation, NY, USA) for all tested muscles (Section 3.4.1). In a randomised fashion, participants then performed one set of ten repetitions for each condition, unilaterally with the dominant limb only. Three minutes resting time were allowed between sets to avoid fatigue. Movement velocity was controlled with a video of every exercise performed at constant velocity; the participants were required to practice mirroring the video without resistance prior to the trials to become accustomed to the velocity, the video was then left running throughout testing as a reference for movement velocity.

6.3.4 Data sampling and processing

EMG (mV) was recorded for the biceps brachii, triceps brachii, rectus femoris, vastus lateralis, vastus medialis and biceps femoris with Trigno wireless electrodes at 1926Hz (Section 5.4.1). Participants performed three MVCs for each muscle before the trials, which were then used to calculate EMG data as a percentage of their maximal contraction (%MVC) to normalise it between participants. Raw EMG data were averaged by root mean square (RMS) and plotted as activation (%MVC) against joint angle (degrees) using EMGworks Analysis software (DelSys Inc., Boston, USA). Peak EMG was recorded as the mean of three peaks, each taken from the first three repetitions, the middle four, and the final three respectively. Total activation was calculated as the integrated RMS EMG curve over a full set of ten repetitions, from the beginning of motion of the first set, to completion of ROM of the tenth set. Total activation for the elastic conditions was normalised to the weight condition by reporting the former as a ratio of the latter. Muscular activation patterns were drawn by calculating the average EMG for every 20° of ROM from three repetitions of each set. A ROM of 180°-20° internal elbow angle, and 120°-0° external knee angle, were split into segments of 20° for the bicep curl and leg extension respectively. Due to the variation of ROM limits between participants, the first and last segments were calculated from their starting/ending position to the next segment. ROM was not restricted to ensure the natural fulfilment of the movements. Joint angles were tracked using 3D motion capture through Qualysis Track Manager at 231Hz.

6.3.5 Statistical Analysis

All data were checked for normality to meet parametric assumptions via a Shapiro-Wilk test. A two-way ANOVA was performed for each pair of methods, with Resistance (T120, W120 or TW120) and ROM (7 levels for biceps, 6 levels for the leg extension) as variables. Significant difference was accepted at alpha = .05 for all statistical tests. LSD post hoc was performed if a significant difference was found. Concentric and eccentric phases were analysed separately.

Peak and total activation were analysed via a repeated measures ANOVA (alpha=.05) with three levels (T, W, TW) and LSD post-hoc where relevant.

6.4 Results

6.4.1 Bicep Curl

6.4.1.1 Biceps Brachii

During the bicep curl, total biceps activation was higher (p=.001) with weights than in all other conditions (Figure 6.1). Peak activation was equivalent in all three conditions, but occurred earlier (90° elbow angle) in the weight condition, later in the elastic condition (50°) and formed a plateau (110°-70°) in the combined condition. Throughout the ROM, tubes and weights elicited significantly different (p<.05) levels of activation: elastic resistance elicited the lowest activation at initial stages of ROM (110-150°) and the highest activation at the end of the ROM in both the concentric (p=.04) and eccentric (p≤.007) phases (Figure 6.3). The combined condition elicited an activation pattern that averaged that of the other two resistances.

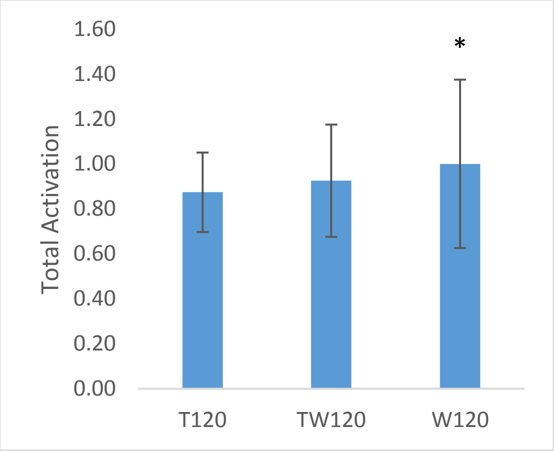


*Figure 6.1 - Mean ± SD (n=21) ratio of total muscular activation of the Biceps Brachii when performing a bicep curl with three different resistance methods (T120, TW120 and W120). * W120 significantly different (p<.001) than all other conditions.*

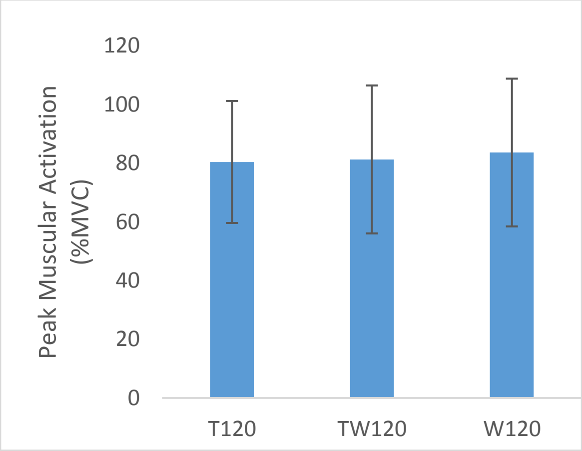


Figure 6.2 - Mean ± SD (n=21) peak muscular activation of the biceps brachii when performing a bicep curl with three different resistance methods T120, TW120 and W120.

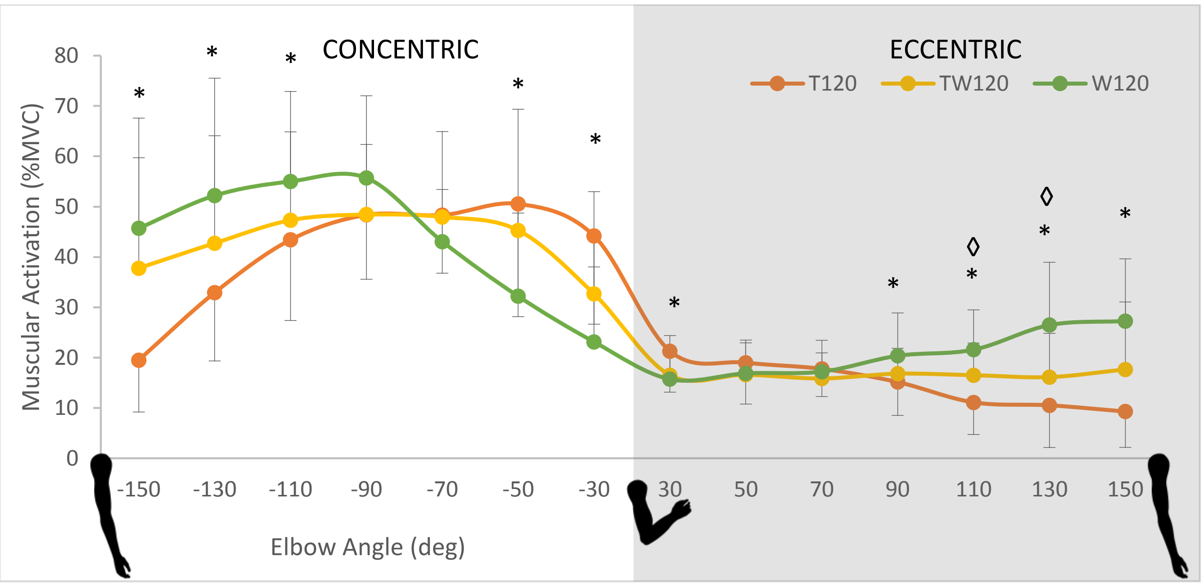


*Figure 6.3 - Mean ± SD muscular activation (n=21) of the biceps brachii muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl performed under three different conditions (elastic tubes, weights, elastic tubes and weights) at 120deg·s^{-1}. * Significant difference (p≤.007) between T120 and W120; ◊ Significant difference between W120 and TW120.*

6.4.1.2 Triceps Brachii

There were no statistical differences in total triceps activation, while peak activation was lowest (p=.004) with weights (Figure 6.4) and occurred earlier in the ROM (90°) with respect to T120 and TW120 (50°). Weight resistance elicited higher activation than tubes at early stages of ROM and lower activation at the end of the eccentric phase (p=.03) (Figure 6.6).

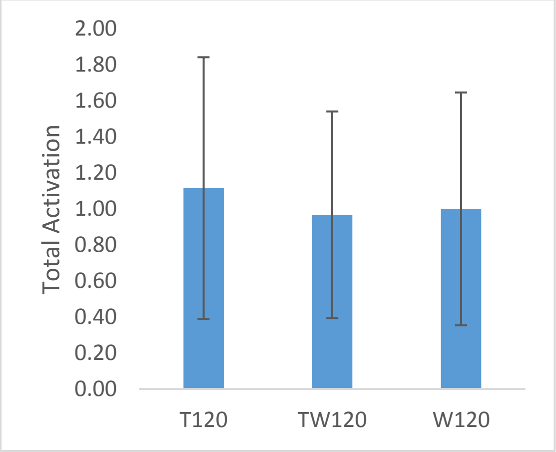


Figure 6.4 - Mean ± SD (n=21) ratio of total muscular activation of the triceps when performing a bicep curl with three different resistance methods T120, TW120 and W120.

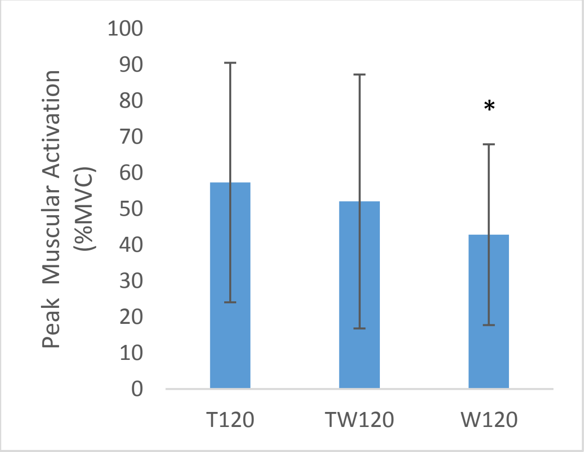


*Figure 6.5 - Mean ± SD (n=21) peak muscular activation of the triceps when performing a bicep curl curl with three different resistance methods T120, TW120 and W120. * W120 significantly lower (p=.004) than all other conditions.*

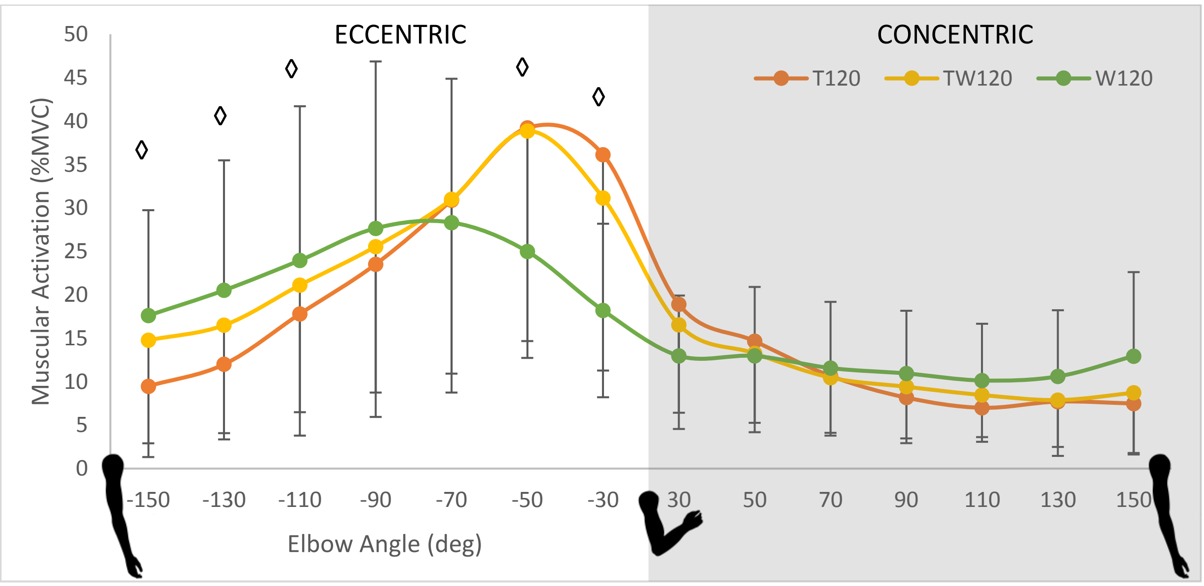


Figure 6.6 - Mean ± SD muscular activation (n=21) of the triceps muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl performed under three different conditions (elastic tubes, weights, elastic tubes and weights) at 120deg·s^{-1}. ◊ Significant difference (p=.03) between TW120 and W120.

6.4.2 Leg Extension

6.4.2.1 Rectus Femoris

There were no significant differences between total activation (Figure 6.7), peak activation (Figure 6.8) or muscular activation patterns (Figure 6.9) of the rectus femoris under any of the three resistance methods.

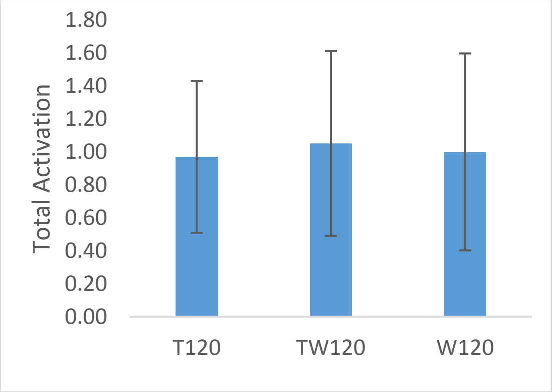


Figure 6.7 - Mean ± SD (n=21) ratio of total muscular activation of the Rectus Femoris when performing a leg extension with three different resistance methods (T120, TW120 and W120).

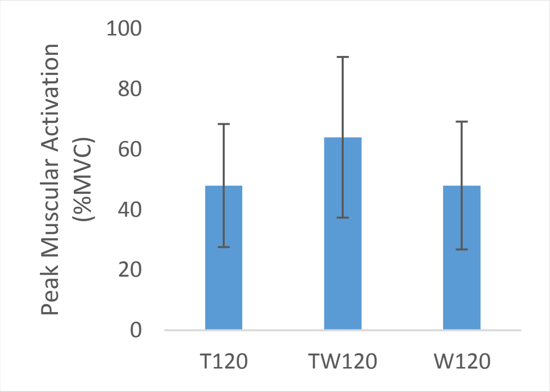


Figure 6.8 - Mean ± SD (n=21) peak muscular activation of the Rectus Femoris when performing a leg extension with three different resistance methods (T120, TW120 and W120).

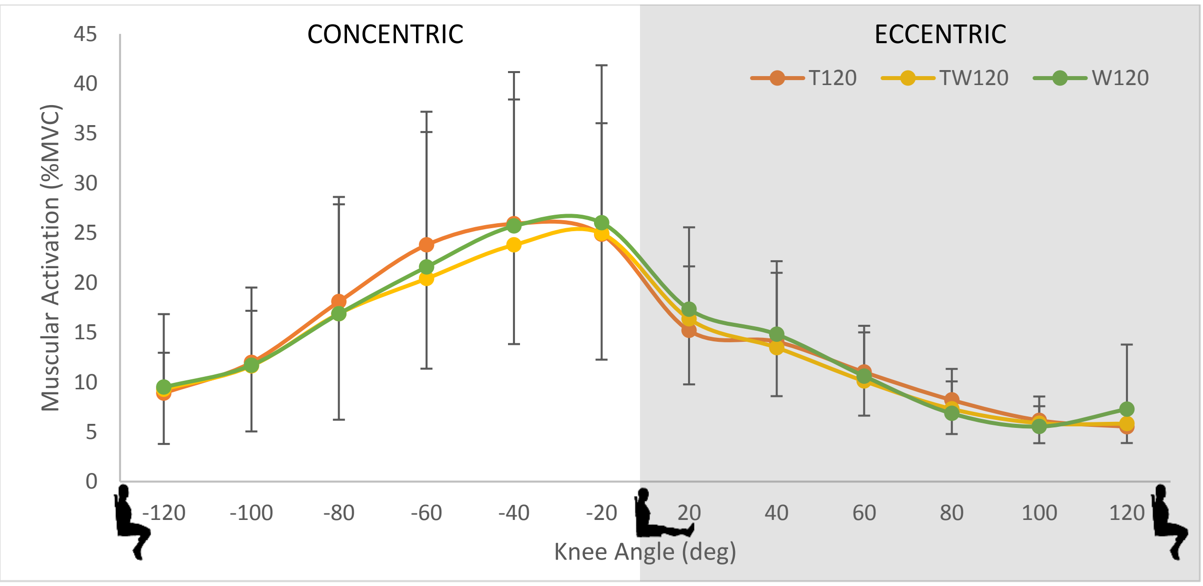


Figure 6.9 – Mean muscular activation (n=22) of the Rectus Femoris per every 20° of ROM, throughout the entire range of motion of a bicep curl performed under three different conditions (elastic tubes, weights, elastic tubes and weights) at 120deg·s^{-1}.

6.4.2.2 Vastus Medialis

There were no significant differences between total (Figure 6.10) or peak (Figure 6.11) vastus medialis activation between resistance methods. The elastic and combined conditions elicited a higher (p<.001) activation than weight resistance throughout most of the concentric phase (Figure 6.12), while only the elastic condition was significantly higher than the weight condition in part of the eccentric phase (p=.009).

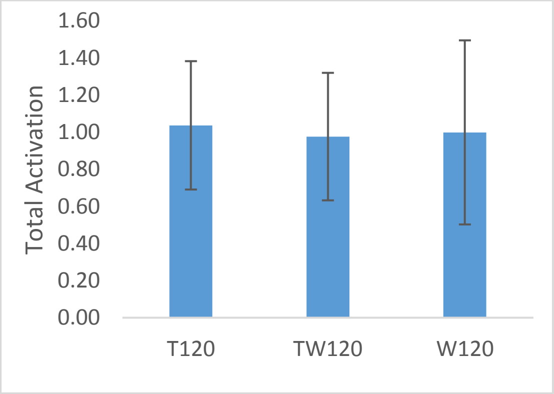


Figure 6.10 – Ratio of total muscular activation(n=21) of the Vastus Medialis when performing a leg extension with three different resistance methods (T120, TW120 and W120).

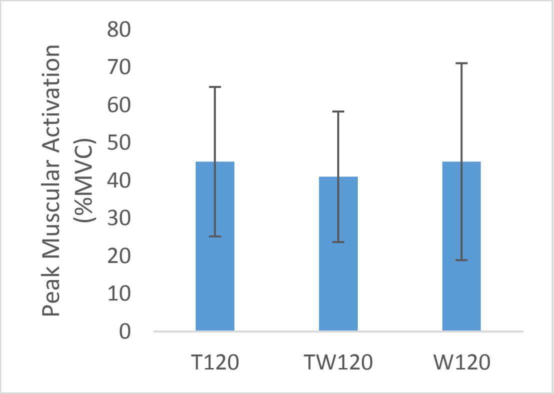


Figure 6.11 - Mean (n=21) peak muscular activation of the Vastus Medialis when performing a leg extension with three different resistance methods (T120, TW120 and W120).

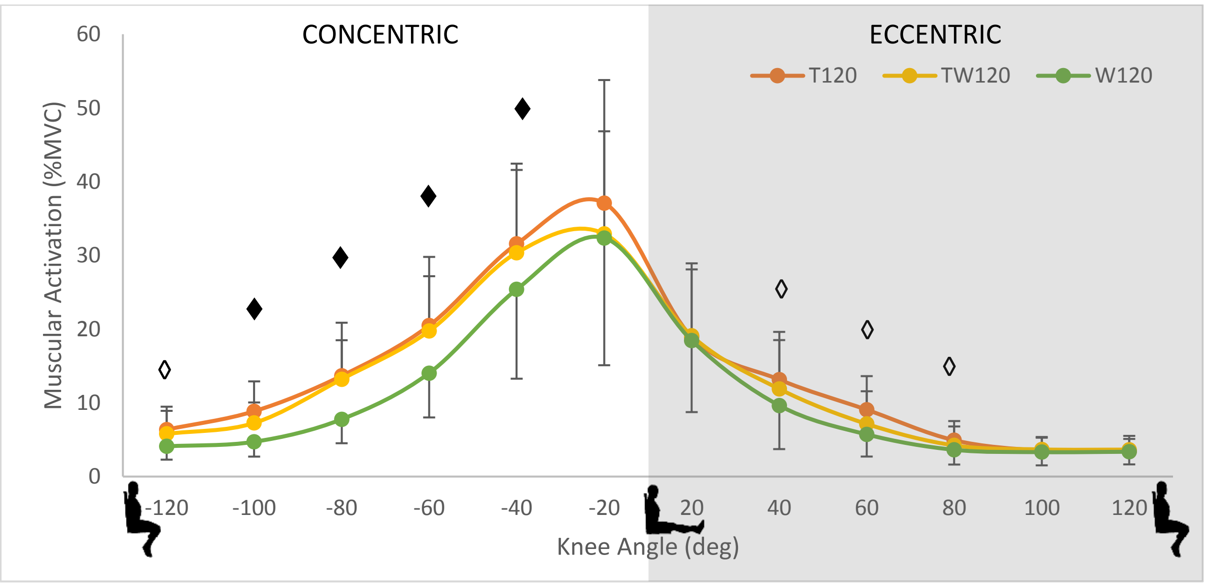


Figure 6.12 - Mean muscular activation (n=22) of the Vastus Medialis per every 20° of ROM, throughout the entire range of motion of a bicep curl performed under three different conditions (T120, W120, TW120) at 120deg·s^{-1}. ♦ W120 is significantly (p<.001) different than all other conditions; ◊ W120 is significantly different (p<.001) than T120.

6.4.2.3 Vastus Lateralis

There were no significant differences in total (Figure 6.13) or peak (Figure 6.14) vastus lateralis activation between resistance methods. Muscular activation of the vastus lateralis (Figure 6.15) was however significantly lower with weights for most of the concentric phase (p=.002); while trends are similar in the eccentric phase but without reaching statistical significance (p=.077).

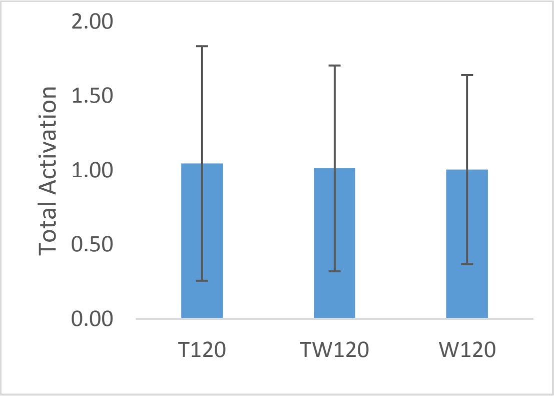


Figure 6.13 - Ratio of total muscular activation (n=21) of the Vastus Lateralis when performing a leg extension with three different resistance methods (T120, TW120 and W120).

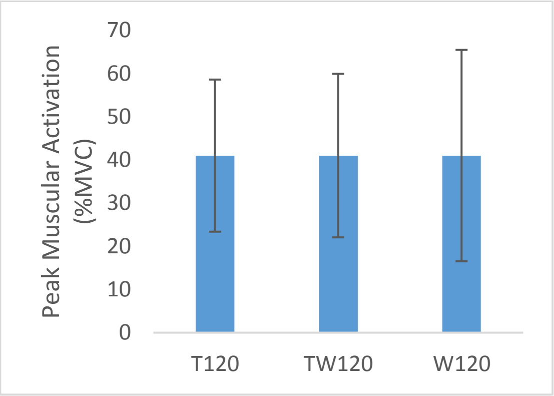


Figure 6.14 - Mean ± SD (n=21) peak muscular activation of the Vastus Lateralis when performing a leg extension with three different resistance methods (T120, TW120 and W120).

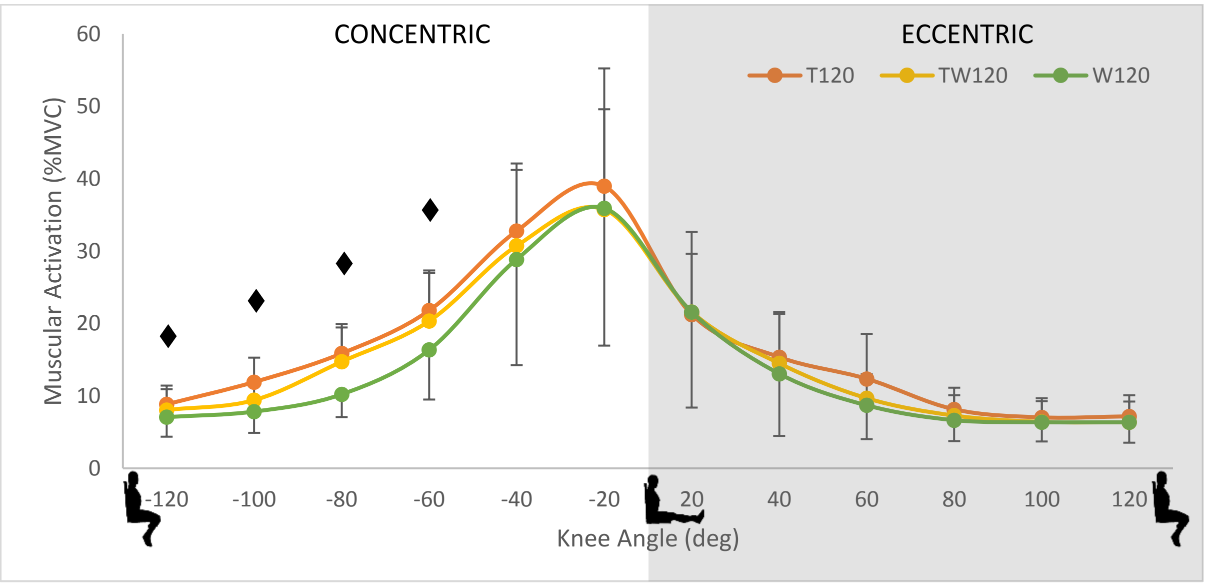


Figure 6.15 - Mean ± SD muscular activation (n=22) of the Vastus Lateralis per every 20° of ROM, throughout the entire range of motion of a bicep curl performed under three different conditions (elastic tubes, weights, elastic tubes and weights) at 120deg·s^{-1}. ♦ Significant difference (p=.002) between W120 and all other conditions

6.4.2.4 Biceps Femoris

There were no significant differences in total activation (Figure 6.16), peak activation (Figure 6.17) or activation patterns (Figure 6.18) of the biceps femoris between conditions.

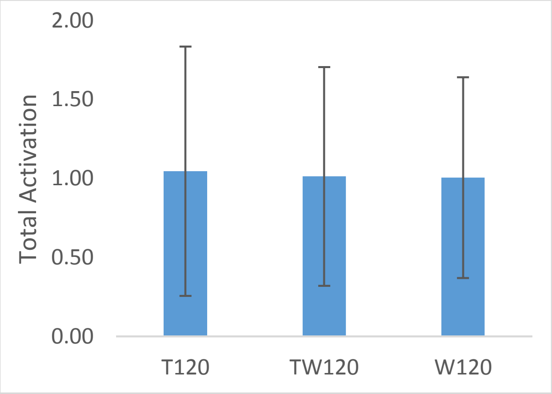


Figure 6.16 - Ratio of total muscular activation (n=21) of the Biceps Femoris when performing a leg extension with three different resistance methods (T120, TW120 and W120).

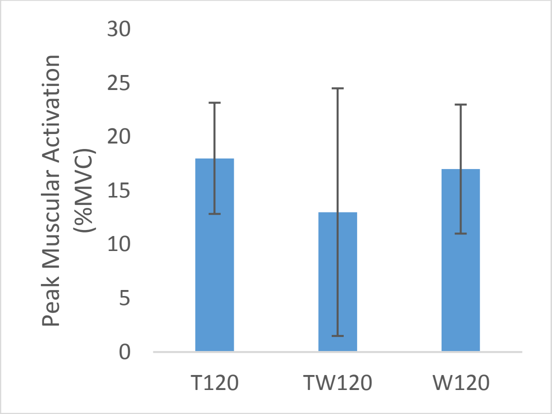


Figure 6.17 - Mean ± SD (n=21) peak muscular activation of the Biceps Femoris when performing a leg extension with three different resistance methods (T120, TW120 and W120).

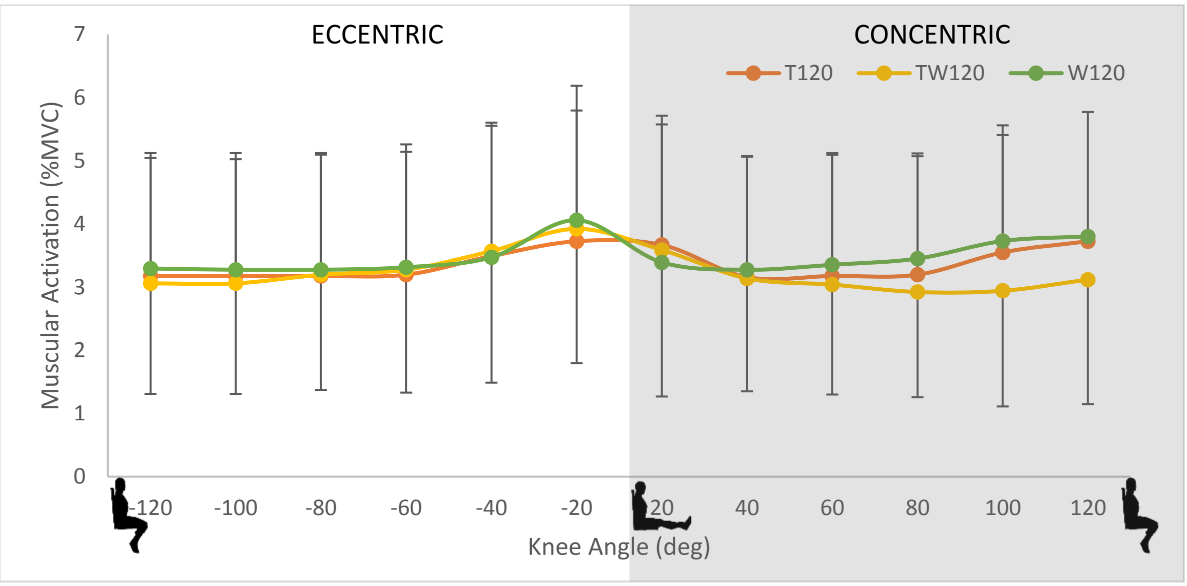


Figure 6.18 - Mean ± SD muscular activation (n=22) of the Biceps Femoris per every 20° of ROM, throughout the entire range of motion of a bicep curl performed under three different conditions (T120, W120, TW120) at 120deg·s^{-1}.

6.5 Discussion

Combining weight and elastic resistance produced muscular activation patterns of the agonist muscles that were most similar to the weight condition at the beginning of the ROM and most similar to the elastic condition at the end of the ROM. In addition, the combined condition elicited muscular activations of the antagonist and synergist muscles that closely reflected those elicited by the elastic condition.

6.5.1 Total activation

Total biceps activation was higher in the weight condition due to an increased activation in the eccentric phase, which was not observed in the elastic or combined conditions. Considering that, at equal loads, eccentric muscle action contributes to strength adaptations as much as the concentric action does (Roig et al., 2008), in the case of the bicep curl, a training programme with weight resistance may produce greater strength increases due to a greater overall activation. This assumption, however, is not reflected in the findings reported by previous intervention studies (Bellar et al., 2001; Anderson et al., 2008). In accordance with Ebben and Jensen's (2002) findings, in this study total muscular activation did not differ between conditions for any muscles except for the biceps brachii. However, although Ebben and Jensen (2002) reported no differences in integrated EMG during a back squat when combining 90% weight load and 10% elastic tension, Anderson et al.'s (2008) findings of substituting only 20% of load with elastic tension in the same exercise is sufficient to provide greater strength gains than 100% weight load stresses the impact of muscular activation patterns and muscle recruitment on strength adaptations. Although reporting total activation gives some insight into the magnitude of muscular responses, it does not enable the investigation of particular forces that might influence muscular overload at less advantageous joint angles, which would in turn enhance myofibrillar adaptations. In addition, it must be considered that increases in 1RM comprise of the contribution of several muscles, where the analysis of synergist activation is also relevant in understanding the influence of resistance methods on strength adaptations. In this study, although total activation of three quadriceps muscles was equivalent in all conditions, muscular activation patterns of the synergist muscles (vastus medialis and lateralis) had a tendency to be more active ($p<.05$) throughout the concentric phase of the leg extension, suggesting a greater contribution to the movement under both the elastic and combined conditions, which could translate to greater increases in 1RM following training. This evaluation indicates that total activation of the agonist muscle is not the sole contributor to strength gains and that muscular activation at specific muscle lengths must also be taken into consideration due to its potential impact on architectural adaptations of the muscle fibres.

6.5.2 Agonist muscles

During the bicep curl, weight and elastic resistance provided similar magnitudes of peak agonist activation that occurred at early and late stages of ROM respectively, while the combined condition provided a plateau of biceps activation that lasted most of the concentric phase (Figure 6.3). Provided that time under tension is a key factor in producing strength adaptations (Burd *et al.*, 2012), it is plausible that a more extended muscular activation throughout the ROM would have contributed to the added strength gains observed in previous intervention studies (Bellar *et al.*, 2011; Anderson *et al.*, 2008). At equal loads, greater time under tension has been found to produce greater protein synthesis than shorter activation times even at low intensities (30% 1RM) (Burd *et al.*, 2012), therefore a resistance method that provides exertion throughout a wider portion of the ROM (TW) would be expected to produce greater strength adaptations than one that produces peak activation only at certain elbow angles (W or T). In this particular study, however, due to the variability of elastic resistance, applied loads were not equivalent throughout the entire ROM. With the current proportions (50% T + 50% W), the combined condition provided an EMG amplitude that averaged that of the two other resistances at any point in the ROM, providing a longer activation, but never reaching the peak values elicited by either of the resistances alone (Figure 6.3). This is observable, not only through the patterns outlined in Figure 6.3, but also from the total biceps activation (Figure 6.1), which was higher for weights due to both a slightly higher peak throughout the concentric phase and a significantly higher activation in the eccentric phase. Implementing higher proportions of elastic and weight resistance (i.e. 70% T + 70% W) in the combined condition should increase the muscular activation throughout the entire ROM, producing a plateau of amplitudes equivalent to those elicited by the other two resistances (100% T, 100% W). It must, however, be considered that by substantially increasing the proportional load provided by each method, the totalling load might become excessive for the participant. Further studies could investigate the optimal combination of the two resistances through both analytical and intervention studies, to determine what proportion of T and W provides a plateau with equal amplitudes to those offered by either resistance, and how the increased time under tension provided by this combination might affect strength adaptations through training.

Furthermore, these findings support Behm's (1991) recommendations of adding elastic resistance to weighted power training to provide muscular overload throughout the entire ROM. The addition of elastic resistance to weight training would be particularly beneficial in providing muscular exertion at phases of movement where the joint position is most advantageous with respect to gravitational forces, but where myofilament overlap is least advantageous (i.e. end of the ROM during a bicep curl or sticking point of a bench press) therefore maximising strength gains.

6.5.3 Synergist muscles

During the leg extension, the combined condition closely reflected the muscular activation patterns and levels observed under elastic resistance alone, providing a higher activation than with weight resistance for both the vastus medialis and lateralis. This suggests that, despite contributing to only half of the applied load, the elastic tension provided was sufficient to cause a destabilization of the knee joint, requiring the recruitment of auxiliary muscles. Therefore, a training programme that combined the use of elastic and weight resistance would effectively recruit synergist muscles, providing the added benefit of increased activation of auxiliary muscles compared to weight resistance, which is particularly desirable in proprioceptive training and joint rehabilitation. In strength training, the enhanced agonist-synergist coactivation offered by the combined resistance may also promote greater improvements in 1RM by inducing strength adaptations in both the agonist and synergist muscles.

6.5.4 Antagonist muscles

A similar behaviour is observed for the antagonist muscle of the bicep curl, where triceps activation patterns and magnitudes in the combined condition were nearly identical to the ones provided by elastic resistance alone, further supporting the assumption that elastic tension contributes to an increased muscle recruitment by way of joint destabilization. In addition, the increasing recoil force of the tubes requires a greater recruitment of antagonist muscles to resist the joint from being extended at final stages of ROM. This indicates that combining the two methods may be as effective as elastic resistance alone in eliciting agonist-antagonist coactivation during exercise, producing adaptations that may enhance joint stability in slow isokinetic and isometric movements (Aagaard *et al.*, 2000).

6.5.5 Conclusion

The combination of elastic and weight resistance therefore offers a combination of the responses elicited by the two methods alone by activating the agonist muscle at both early at late stages of the ROM, not only providing muscular exertion at all muscle lengths, but also offering a plateau in muscle activation that increases the time under tension of the agonist muscle. These characteristics, coupled with the added recruitment of synergist muscles, may contribute to greater strength gains following resistance training with combined resistances rather than weight resistance alone.

Provided that all three methods elicited very different patterns of agonist activation, a comparison of the effects of either of the three methods on isokinetic and isometric strength would provide better understanding of the effects of activation patterns on long term muscular adaptations and on the possible applications of elastic resistance, whether used alone or in combination with weights. In addition, due to the impact that a greater time under tension may have on muscle fatigue, and ultimately on adaptations, the impact of elastic resistance on fatigue should also be considered.

Chapter 7

The repetition effect of elastic and weight resistance exercise

7.1 Abstract

INTRODUCTION: Muscular fatigue is an important aspect of training and has been thoroughly investigated in a variety of exercise contexts, although very few studies have so far considered the effects of elastic training on repeated exercise. Spectral analysis of electromyographic data enables researchers to detect the onset of fatigue earlier than its manifestation through a decline in performance, permitting an indirect analysis of physiological responses to exercise without the need to reach momentary muscular failure. The literature has so far substantiated that an increase in EMG amplitude and a decrease in EMG frequency are indicators of the onset of muscular fatigue and occur before any changes in force output can be detected. This study aims to investigate the repetition effect of elastic resistance in comparison to free weights during two common strength exercises.

METHODS: Moderately active males (n=8; age=25±6 years) performed 30 bicep curls and leg extensions with 6kg weights and an equivalent elastic resistance (Silver Thera-band® tubes) at an average angular velocity of 120deg·s^{-1}. Muscular activation of the biceps, triceps, rectus femoris and vastus medialis was recorded with Trigno wireless electrodes (1926Hz) and 3D-motion capture with Qualysis Track Manager (231Hz). Peak EMG amplitude (PA) and mean EMG frequency (MF) were recorded for every 5 repetitions and a linear regression was applied to determine rate of change. A paired t-test was performed on the initial and final values and on the slope of each parameter between resistances.

RESULTS: During the bicep curl, the biceps exhibited rates of change of PA (b_T=2.79, b_W=2.42) and MF (b_T=-4.28, b_W=-5.29) which did not differ between resistances. The triceps exhibited higher ($p<.05$) magnitudes of initial PA and MF under elastic resistance, and a decrease in MF under both resistances (b_T=-3.51, b_W=-2.78). Increases in triceps PA (b_T=-.95, b_W=1.05, p=.025) were not observed in the elastic condition due to a decrease in range of motion (ROM) at the end of the trial.

During the leg extension, there were no differences in rectus femoris PA or MF between conditions, both with negligible rates of change. The vastus medialis exhibited higher ($p<.001$) magnitudes of MF throughout the trial, also with no prominent trend in rate of change in either condition.

DISCUSSION: The agonist muscles of both exercises produces similar responses to repeated exercise under both resistances, suggesting prolonged exercise under elastic and weight resistance result in similar physiological responses of agonist muscles. The higher magnitude of triceps EMG reading in the elastic condition demonstrated that antagonist muscle activation remains consistently higher during repeated bicep curls under elastic resistance, although a decrease in PA suggests that participants must sustain full ROM if wanting to fully activate the triceps throughout the trial. The higher MF of the vastus lateralis also demonstrated that synergist muscles of the leg extension remain more active under elastic resistance and suggests that, at greater loads, the vastus medialis would fatigue at higher rates under elastic resistance.

In summary, at comparative loads, elastic and weight resistance effect similar changes in electromyographic indicators of fatigue of agonist muscles and exhibited sustained levels of higher agonist and synergist activation after 30 repetitions.

7.2 Introduction

Fatigue is described as a reduction in the force generating capacity of the neuromuscular system, which is characterised by a progressive decline of performance during sustained activity (Allen *et al.*, 2008) eventually reaching momentary muscular failure (Enoka and Stuart, 1992). Peripheral muscular fatigue can involve high or low frequency fatigue, with a significant but fast recovering loss of muscle force in the former, and a slow recovering of low frequency muscle function in the latter (Inguchi et al., 2008; Keeton and Binder-Macleod, 2006). In both cases, the observed decline in performance is reversible and can be caused by a number of factors, including muscular activation pattern, exercise intensity, velocity, duration of physical activity and subject motivation (Barry and Enoka, 2007). It is common practice to use the point of muscular failure as evidence of fatigue, although fatigue is not an instantaneous phenomenon and would be best studied in its entirety, as a gradually developing occurrence. Hence, De Luca (1997) proposed using spectral analysis of electromyographic changes to detect and assess the gradual onset of fatigue that occurs during repeated or sustained contractions.

Measuring the effects of fatigue is most challenging. Aside from the impracticality of having to reach failure several times when testing different methods, the use of force output as a measure of fatigue presumes that various muscle groups around a joint act as a unit, when in fact different muscles contribute to the movement in varying proportions and therefore respond differently to repetitions. Finally, the point of muscular failure is affected by subject motivation as well as physiological factors, which cannot be accounted for through mechanical observation alone. The onset of fatigue is in fact observed earlier through electromyography than it is through mechanical changes in force output (Roberts *et al.*, 2006; De Luca, 1997), enabling researchers to investigate some effects of exercise on physiological mechanisms of contraction during high frequency fatigue protocols, without having to reach exhaustion. Although determining muscle function through EMG, rather than through a visible impairment in physical performance, is a weaker indicator of the onset of fatigue, an electromyographic study of fatigue allows a more detailed insight into the responses of specific muscles. Examining the early onset of fatigue rather than full fatigue also enables the testing of various methods in a single session, which prevents discrepancies in EMG signals that are observed when having to perform EMG readings on separate days.

It has been extensively observed that muscular fatigue produces EMG readings of increased amplitude and decreased frequency. Decreases in EMG frequency have been linked to a disruption in the Na^+-K^+ equilibrium across the sarcolemma, which affects the excitability of muscle fibre membranes resulting in lower motor unit firing rates (vanDieen *et al.*, 2009; Fortune and Lowery, 2007; Juel 1988); while increases in EMG amplitude have been linked to a decrease in intracellular pH, which alters the contractility of the fibres, effecting a recruitment of additional motor units in order to meet the demand for power output and resulting in a higher reading of muscular activation without changes in force output (Camic *et al.*, 2010; Enoka and Stuart, 1992; Moritani *et al.*, 1982). The onset of muscular fatigue is proposed to induce adaptive increases in central neural drive, improving skeletal muscle recruitment, and in biochemical processes that enhance myofibril contrarily, hence improving performance (Noaks, 2000). Therefore, determining the repetition effect of elastic resistance on different muscle groups may help better predict the outcomes of elastic resistance training.

The research to date on elastic training lacks consensus on the effects of this resistance method on overall muscular activation and therefore makes it difficult to predict muscular responses to continuous exercise under elastic tension. As for the findings so far reported in this project, it can be hypothesised that distinct muscle groups may respond differently to fatigue, where muscles that were observed to be more active under elastic resistance (eg. synergist muscles) may be more susceptive to the repetition effect in this condition. A differing rate of fatigue between conditions would confirm speculations that elastic resistance could induce greater strength adaptations in auxiliary muscles with respect to weights, establishing their beneficial effect in engaging secondary muscles more than weights. On the other hand, if the fatigue of auxiliary muscles increases at higher rates than agonist muscles, this could induce a breakdown in technique due to overload of secondary muscles, increasing the risk of fatigue-related injuries.

To date, only one publication has investigated the effects of elastic resistance on muscular fatigue, reporting no differences in biceps EMG frequency or amplitude compared to weight resistance after bench elbow flexions to failure (Melchiorri and Raindoli, 2011). Melchiorri and Raindoli (2011) recorded a higher initial EMG frequency and a greater decline in fibre conduction velocity under elastic resistance, suggesting a larger metabolic effect in this condition. Melchiorri and Raindoli (2011) linked the probable increase in metabolic effect to a possibly increased eccentric muscular activation under elastic resistance. The previous chapters of this project have however substantiated that elastic resistance does not elicit a higher eccentric activation of the agonist muscles at any of the three tested velocities, indicating that other factors may have affected Melchiorri and Rainoldi's (2011) results.

Given the paucity of research on the effects of repeated exercise under elastic resistance on EMG responses, there is a need for further investigation into this aspect of elastic training to better inform professionals on the implementation of different training strategies. This study aims to investigate the effects of elastic resistance on repeated contractions under moderate load, at an angular velocity that reflects the one used during self-paced exercise.

7.3 Methods

7.3.1 Participants

Eight moderately active males (age =25 ± 6 years; stature = 178 ± 6 cm; mass = 74 ± 11 kg) were recruited for the study on a voluntary basis. All participants signed an informed consent and PAR-Q form before testing (Appendix A). The study was approved by Kingston University Faculty's Ethics committee in line with the declaration of Helsinki.

7.3.2 Conditions

Participants performed each exercise with two different resistance methods (weights and elastic tubes) at an average angular velocity of $120 \text{deg} \cdot \text{s}^{-1}$. For the weight condition (W120) 6kg dumbbells were used for the bicep curls and 6kg ankle weights were used for the leg extension. Elastic tubes of equivalent load (silver Thera-band® tubes reduced by 10% of their initial length) were used for the elastic condition (T120).

7.3.3 Procedures

Before testing, the participant's skin was thoroughly cleaned and Trigno surface wireless electrodes (DelSys Inc., Boston, USA) were positioned on each muscle in accordance with SENIAM guidance (SENIAM, 2012) (Section 3.4.1). Retroreflective markers were then placed on bony landmarks of exercising limbs for use during 3D motion capture in order to record joint angles (Section 3.4.2).

Participants warmed up with dynamic exercise for 5 minutes, which included jogging and dynamic stretches of the arms and legs. Participants then performed unilateral isometric maximal voluntary contractions (MVC) on a Biodex Dynamometer (Biodex Corporation, NY, USA) for all tested muscles (Section 3.4.1). In a randomised fashion, participants then performed 30 bicep curls and 30 leg extensions with the dominant limbs with T120 and W120. Ten minutes resting time were allowed between sets to avoid fatigue (Allen *et al.*, 2008). Movement velocity was controlled with a video of each exercise performed at constant velocity; the participants were required to practice mirroring the video without resistance before the trials to become accustomed to the velocity, the video was then left running throughout testing as a reference for movement velocity.

7.3.4 Data sampling and processing

EMG (mV) was recorded for the biceps brachii, triceps brachii, rectus femoris and vastus medialis with Trigno wireless electrodes at 1926Hz (Section 3.4.1). Participants performed three MVCs for each muscle before testing, which were then used to calculate EMG data as a percentage of their maximal contraction (%MVC) in order to normalise data between participants. Raw EMG data was processed by root mean square (RMS). The software EMGworks Analysis was used to calculate EMG frequency (Hz) from raw data with a window length of .125s and overlap of .0625s. Peak EMG amplitude (PA) and EMG mean frequency (MF) were recorded for each interval of 5 repetitions. Linear regression was applied to each participant's data and averaged to identify the rate of change of each parameter.

7.3.5 Statistical Analysis

All data was checked for normality to meet parametric assumptions via a Shapiro-Wilk test. Linear regression was applied to each participant's data, the slopes from all participants' data was then averaged to identify the mean rate of change of each parameter (PA and MF). Paired t-tests were performed to determine differences in PA and MF rates of change between resistance methods, and between initial and final values of those same parameters between conditions. Significant difference was accepted at alpha = .05.

7.4 Results

7.4.1 Bicep Curl

7.4.1.1 Biceps Brachii

Increasing trends in PA (Figure 7.1) were not significant for either method (p_T=.08, p_W=.136), while both methods showed evidence of fatigue with a significant (p<.001) decrease in MF (Figure 7.2). Between conditions there were no differences in rates of change or initial values of biceps PA (b_T=2.79, b_W=2.42) or MF (b_T=-4.28, b_W=-5.29). Variance was very low for all bicep curl data (R^2>.7).

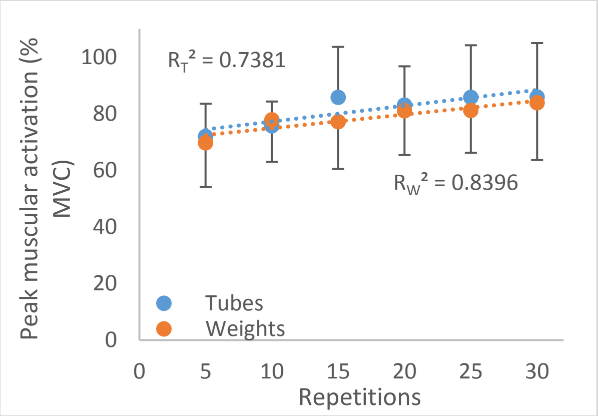


Figure 7.1 - Mean ± SD (n=8) peak Biceps Brachii activation per every five repetitions of Bicep Curls.

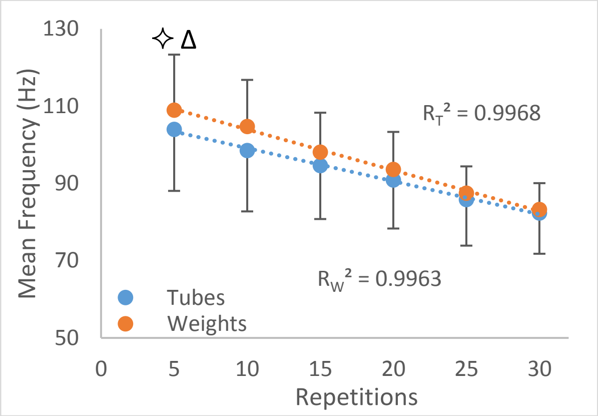


Figure 7.2 - Mean ± SD (n=8) EMG frequency of Biceps Brachii activation per every five repetitions of Bicep Curls. Δ Significant difference (p<.001) between the first and last values (T) ✧ Significant difference (p<.001) between the first and last values (W).

7.4.1.2 Triceps Brachii

Triceps PA remained higher (p<.05) under elastic resistance throughout the trial, while values decreased significantly (p=.016) with weights (b_T=-.95, b_W=1.05; p=.025) (Figure 7.3), although there was a high variance in the data (R^2=.3). Initial values of MF (Figure 7.4) were also higher (p=.04) under elastic resistance, while rates of change (b_T=-3.51, b_W=-2.78) were not significantly different between conditions and exhibited low variance (R^2>.9). MF decreased significantly (p≤.001) for both conditions, demonstrating evidence of fatigue.

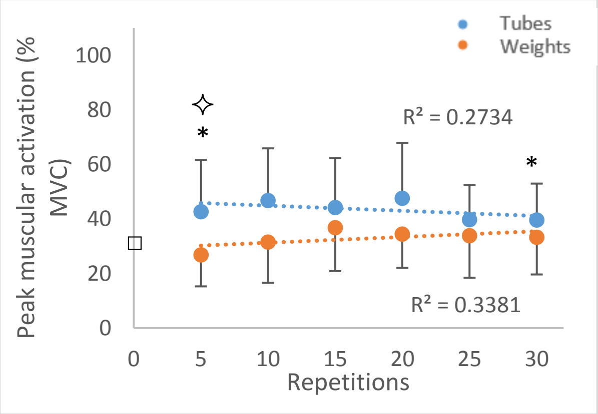


*Figure 7.3 - Mean ± SD (n=8) peak Triceps Brachii activation per every five repetitions of Bicep Curls. □ Significant difference (p=.025) between slopes; *Significant difference between tubes and weights for initial (p=.001) and final (p=.006) PA values. ✧ Significant difference (p<.001) between the first and last values (W).*

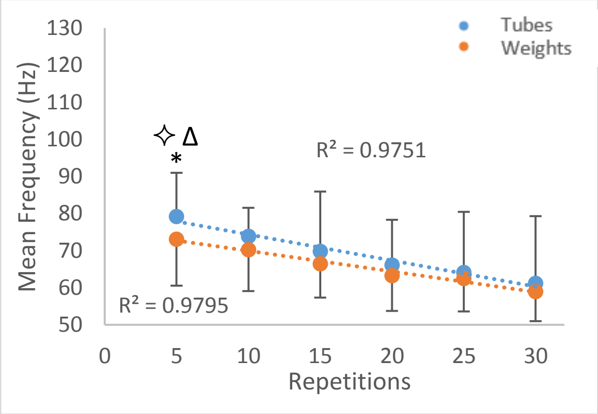


*Figure 7.4 - Mean ± SD (n=8) EMG frequency of Triceps Brachii activation per every five repetitions of Bicep Curls. *Significant difference (p=.04) between initial frequency values. Δ Significant difference (p<.001) between the first and last values (T) ✧ Significant difference (p=.001) between the first and last values (W).*

7.4.2 Leg Extension

7.4.2.1 Rectus Femoris

There were no differences between resistance methods in rates of change of PA (Figure 7.5) (b_T=1.81, b_W=.09), MF (Figure 7.6) (b_T=-.65, b_W=-1.00) or initial and final values of either parameter. Neither PA or MF demonstrate evidence of fatigue. PA data exhibited high variance (R^2<.5) while MF exhibited lower variance (R^2>.5).

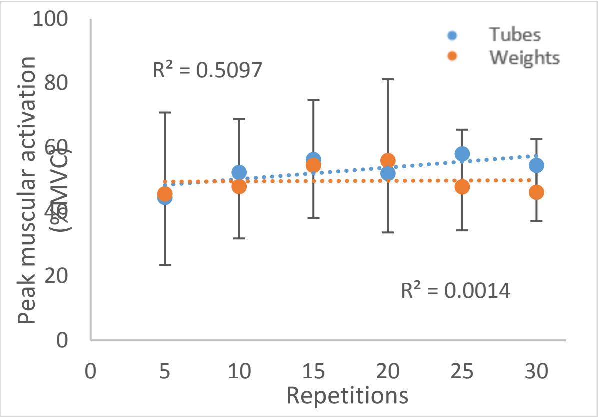


Figure 7.5 - Mean ± SD (n=7) peak Rectus Femoris activation per every five repetitions of Leg Extensions.

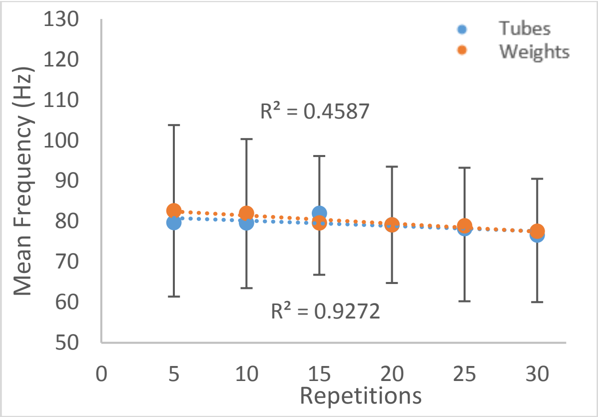


Figure 7.6 - Mean ± SD (n=7) EMG frequency of Rectus Femoris activation per every five repetitions of Leg Extensions.

7.4.2.2 Vastus Medialis

There were no significant differences in PA (Figure 7.7) (b_T=1.01, b_W=.58) or MF (Figure 7.8) (b_T=-.28, b_W=-.25) rate of change of the vastus medialis, demonstrating no evidence of fatigue. MF remained higher (p<.001) under elastic resistance throughout the trial. All data sets for the vastus medialis exhibited high variance (R^2<.4).

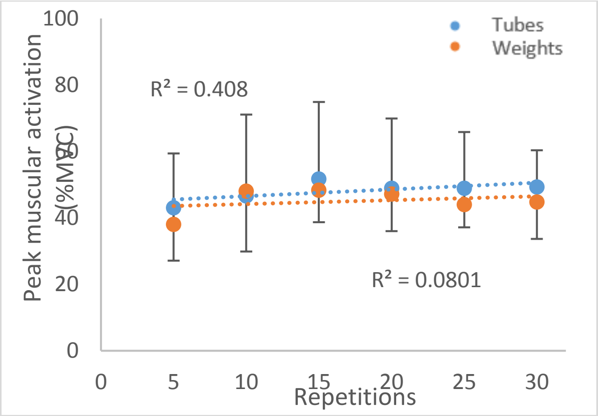


Figure 7.7 - Mean ± SD (n=7) peak Vastus Medialis activation per every five repetitions of Leg Extensions with two different resistance methods (elastic tubes and weights).

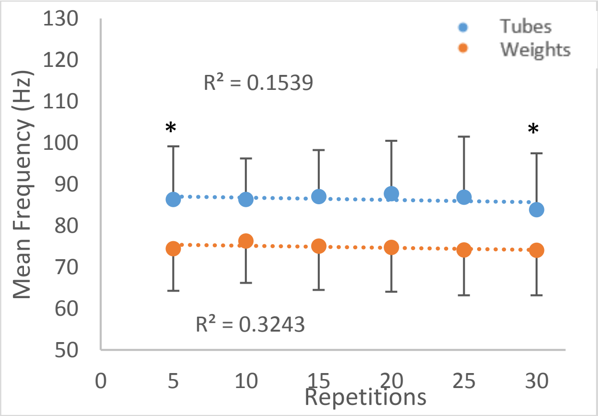


*Figure 7.8 - Mean ± SD (n=7) EMG frequency of Vastus Medialis activation per every five repetitions of Leg Extensions with two different resistance methods (elastic tubes and weights). *Significant difference (p<.001) between tubes and weights for initial and final MF values.*

7.4.3 Range of motion

Range of motion decreased significantly for the bicep curls where, at the end of thirty repetitions, the elastic condition displayed smaller initial elbow angles (p=.044) and larger final elbow angles (p=.001), while the weight condition exhibited a decrease in initial elbow angles only (p=.026). There were no significant changes in ROM during the leg extension.

*Table 7.1 - Range of motion for the first and last 5 repetitions, determined as elbow angle during the bicep curl and knee angle during the leg extension. * Significant difference (p<.05) from value from the first 5 repetitions.*

		TUBES		**WEIGHTS**	
		Start-ROM	End-Rom	Start-ROM	End-ROM
BICEP CURL	First 5 reps	143° ± 10	34° ± 4	144° ± 10	31 ± 5°
	Last 5 reps	137° ± 8*	40° ± 5*	133° ± 13*	34 ± 6°
LEG EXTENSION	First 5 reps	67° ± 7	169° ± 11	70° ± 6	169° ± 10
	Last 5 reps	66° ± 6	168° ± 13	71° ± 7	170° ± 12

7.5 Discussion

The main findings of this study reveal that agonist muscles produce similar responses to repeated exercise with elastic and weight resistance, while auxiliary and antagonist muscles exhibited a tendency to fatigue more quickly during elastic resistance exercise.

7.5.1 Agonist muscles

Both agonist muscles (biceps brachii, rectus femoris) exhibited an increase in peak amplitude and a decrease in mean frequency, which are both indications of a gradual onset of fatigue (Camic *et al.*, 2010; Roberts *et al.*, 2006; De Luca, 1997). The changes were only statistically significant for the bicep curl due to the higher relative load (~70%MVC) compared to the leg extension (~40%MVC), where the lighter load was also the likely cause of the higher variance in the data. This was a strong limitation of this study. The load (6kg) was chosen to maintain consistency with the previous chapters in this thesis; however, due to the superior strength of the leg muscles, greater loads should have been implemented for this exercise throughout the thesis and particularly in this study.

In accordance with Melchiorri and Raindoli’s (2011) findings, the agonist muscles of both exercises responded similarly to the trial, with no differences between conditions in either initial values or rates of change of peak amplitude or mean frequency. Previous chapters (Chapters 4, 5) of this project reported equal overall activation of the agonist muscles with both resistance methods during the first ten repetitions; according to this study, agonist muscle activation continues to be equal after thirty repetitions. The fact that peak activation occurred at different stages of ROM between resistance methods (Chapter 5) did not seem to affect indicators of fatigue over time, indicating that rate of fatigue is dependent on work volume and magnitude of peak activation, independent of where the peak occurs along the length-tension relationship curve.

Melchiorri and Rainoldi (2011) also reported higher rates of change in biceps conduction velocity under elastic resistance, which was not measured in this study. The authors suggested that the higher rate of change may have been related to a higher biceps activation during the eccentric phase under elastic resistance. So far, Cronin *et al.* (2003) have been the only authors to report evidence of higher eccentric activation under elastic resistance during a jump squat, which involved multiple joint movements, a jumping and landing/braking action. The last phase of movement (braking) produced a higher eccentric activation under elastic resistance, where more force was required in counteracting the greater momentum generated by the elastic tubes during the landing phase. The kinematics of a jump squat differ substantially from single joint exercises such as the ones described in this chapter and in Melchiorri and Rainoldi (2011), which would account for the difference in muscular activation patterns observed in either study. No other papers on elastic training found evidence of higher muscular activation during the eccentric phase (Jakobsen *et al.*, 2014; Aboodarda *et al.*, 2013, 2011; Matheson *et al.*, 2001), and all findings so far reported in this project have also clearly demonstrated that, at comparative loads and comparative directions of applied load, elastic resistance does not elicit a higher eccentric activation of agonist muscles and remains significantly lower even at high movement velocities, where it only increases with weight resistance (Chapter 5). The findings reported in Chapter 5 also demonstrated that, due to their low resistance at initial phases of movement, elastic tubes allow for greater accelerations. Considering that a higher fibre shortening velocity is associated with a higher MF (Aagaard *et al.*, 2000; van Cutsem *et al.*, 1998), and that Melchiorri and Rainoldi (2011) only controlled for cadence but not for angular velocity throughout the movement, it is possible that the higher MF reported by the authors may be associated with higher initial movement velocities in the elastic condition. Finally, Melchiorri and Rainoldi (2011), contrarily to this study, limited the participants' ROM to 100-35° elbow angle. It was evident in Chapter 4 that at angles greater than 90°±10, muscular activation was higher with weight resistance with respect to elastic resistance, while the opposite is true for elbow angles smaller than 50°±10. The greater fatiguability in the elastic condition

Considering that changes in EMG parameters are a result of changes in metabolic by-product concentrations and electrochemical gradients at cellular level (Camic *et al.*, 2010; De Luca, 1997), it can be inferred that, at comparative loads, elastic and weight resistance produce similar physiological effects on agonist muscles during repeated contractions. Evidence of this is found in recent studies by Aboodarda *et al.* (2011, 2012), who reported that moderate to high intensity elastic resistance exercise exhibited similar responses in physiological indicators of muscle damage to exercising with a nautilus machine, including similar increases in plasma creatine kinase, lactate, growth hormone, testosterone and muscle signal on *T2 weighted MRI*, which were all indicative of similar physiological responses to either resistance method. Increases in muscular contraction by-products, like the ones observed by Aboodarda *et al.* (2011, 2012), may have therefore mediated a disruption in membrane excitability and an impairment in the release of Ca^{2+} from the sarcoplasmic reticulum (Enoka and Stuart, 1992; Moritani *et al.*, 1982), hence requiring the recruitment of additional motor units to match the required work load (Moritani *et al*,. 1982) resulting in the increased amplitude observed in this study (Camic *et al.*, 2010; Petrofsky, 1979).

7.5.2 Synergist muscle

Vastus medialis MF values were higher under elastic resistance throughout the entire trial but did not exhibit any indications of fatigue under either resistance. The higher magnitude of MF under elastic resistance reflects previous findings, where the vastus medialis exhibited a higher time under tension at medium and high velocities (Chapter 5), consolidates previous speculations of joint destabilization under variable resistance, which appears to be maintained after thirty repetitions. As mentioned for the rectus femoris, rates of change were not prominent due to the low load (~40%MVC), but considering that time under tension is directly proportional to neuromuscular fatigue (Tran *et al.*, 2006) and given the higher magnitude of MF under elastic resistance, it can be speculated that this method would produce a faster onset of fatigue with respect to weight resistance at loads higher than 60%MVC. Despite the very high variance in the PA data, which can also be attributed to the low load, PA increased at faster rates in the elastic condition. Although the PA data is not sufficiently robust to draw a conclusion, if combined with the aforementioned observations on MF data, these trends suggest a high likelihood that the vastus medialis would fatigue at higher rates under elastic resistance than with weights. If this can be confirmed, the higher rate of fatigue of synergist muscles with elastic resistance would result in greater strength adaptations with respect to weight training. Further studies are required to confirm these claims.

7.5.3 Antagonist muscle

The higher triceps peak amplitude and mean frequency observed in the elastic condition both indicate a higher overall activation of the triceps throughout the trial, which is also a reflection of previous findings where peak triceps activation was consistently higher under elastic resistance (Chapter 5). The significant decline in MF indicates that the triceps became increasingly fatigued under both resistances, although this finding appeared to be contradicted by a decrease in peak amplitude in the elastic condition, which can be explained by a decline in ROM observed only in this condition (Table 7.1). Given that peak triceps activation occurs at elbow angles between 40 - 20° (Chapter 4, Figure 4.6), not reaching small elbow angles at the end of the thirty repetitions may have restricted the triceps from reaching peak activation. Participants appear to have made a lesser effort to complete the ROM in the elastic condition due to the increasing tension at latter stages of movement, hence resulting in lower peak triceps activation. A closer observation of the biceps PA also shows that PA increased at high rates for the first 15 repetitions (Figure 7.1), at which point it remained constant. This could also be related to a decline in ROM, given that biceps peak activation also occurred at elbow angles below 40° (Chapter 4, Figure 4.3). Despite the decrease in PA, especially for the triceps, MF rates of change still provide an electromyographic indication of repetition effect which matched that of the weight condition. It can be therefore inferred that, should participants sustain full ROM, the triceps muscle, and possibly even the biceps, may fatigue at a faster rate under elastic resistance, in which case elastic training would prove more beneficial than weights in promoting agonist-antagonist co-activation, therefore enhancing proprioception and inducing concomitant strength adaptations in antagonist muscles during resistance training. Further studies with controlled ROM are required to confirm this suggestion.

7.5.4 Conclusion

The findings reported in this study indicate that elastic and weight resistances induce fatigue of the agonist muscle at similar rates and, while changes in peak amplitude and mean frequency were not prevalent in the synergist and antagonist muscles observed, the sustained higher magnitude of activation of these muscles in the elastic condition suggests that they may fatigue at higher rates under elastic resistance compared to weight resistance.

It has been so far established that peak muscular activation occurs at different joint angles under elastic and weight resistance. But, provided that full ROM is maintained, the location of the peak does not influence the rate of fatigue of agonist muscles. Based on these findings, it can be speculated that, although elastic and weight training may produce equivalent gains in isokinetic strength, increases in isometric strength at specific joint angles may differ. A longitudinal training study is needed to corroborate these assumptions.

Chapter 8

Effects of dynamic elastic and weight resistance training on isometric strength gains at different elbow angles

8.1 Abstract

INTRODUCTION: Elastic and weight training were found to exert the agonist muscle at opposing phases of the range of motion (ROM) (Chapters 4,5) which, following a training programme, could affect specific levels of strength adaptation at different joint angles. Consequently, elastic tubes and weights have also been hypothesised to produce greater strength adaptations when used in combination (Chapter 6). The aim of this study was to determine whether a strength training intervention with elastic tubes, weights, or a combination of the two had different impacts on strength gains at specific phases of ROM.

METHODS: Seven males (age 22 ± 8 years, stature 178 ± 7 cm, mass 76 ± 20 kg) and 12 females (age 26 ± 9 years, stature 162 ± 8 cm, mass 58 ± 12 kg,) who were either sedentary or lightly active were randomly assigned to either elastic training (T), weight training (W) or combined elastic and weight training (TW). They completed an 8 week home-based training programme which consisted of bicep curls, starting with 3x10 repetitions and incrementing to 3x25 repetitions in the final two weeks of training. Arm flexion isometric strength was measured before and after the training programme with a Biodex Dynamometer (Biodex Corporation, NY, USA) at three different internal elbow angles (150°, 90°, 40°); pre and post isokinetic peak torque were measured on the Biodex at 120deg·s^{-1} and pre and post intervention biceps girth was measured at the muscle belly with a flexed arm at 90° internal elbow angle. A mixed model ANOVA was used to determine significant differences in the data (alpha = .05).

RESULTS: Biceps girth increased significantly ($p<.05$) for all groups after the eight weeks, with no effect of resistance method between groups. Isokinetic strength increased ($p<.05$) for the non-dominant arm in the T and W groups only. Isometric strength increased for both the dominant (D) and non-dominant (ND) arms at all angles (D: $p<.001$; ND: $p=.002$). Within subjects, isometric strength gains differed between elbow angles (D: $p=.005$; ND: $p<.001$), where the T and TW groups obtained the greatest gains at 40°, the W group obtained greatest gains at 150° and all groups obtained the lowest gains at 90°. Between subjects, trends displayed greater isometric gains at 150° with T, greater gains at 40° with W and greater gains at 90° with TW, although these did not reach statistical significance due to a low effect size.

DISCUSSION: Significant isokinetic strength gains with T and W demonstrate that both methods are equally effective in producing strength adaptations, while the lack of significant changes in TW suggest that combining 50% elastic and 50% weight load is not sufficient to obtain the same results as using the two methods alone, and that a higher proportion of each load should be used in order to obtain comparable results in isokinetic strength.

Isometric strength gains reflected previous findings in muscular activation patterns where T, which portrayed peak activation at the end of the ROM (Chapters 4,5), produced greater isometric strength gains at 40° elbow angle; W, which portrayed peak activation at the beginning of the ROM, produced the greatest gains at 150° and TW produced the greatest gains at 90° compared with the other methods. These changes were not statistically significant due to the low effect size of the study, however trends are sufficiently evident to be considered of importance in the discussion of the results. These findings suggest that elastic and weight training may effectively produce differing architectural adaptations, which result in a shift in peak force generation at different joint angles and may highly impact performance and injury risk if implemented in the long term.

8.2 Introduction

The previous chapters of this thesis have so far demonstrated that elastic and weight resistances can elicit comparable magnitudes of mean and peak activation of the agonist muscles, but they differ substantially in specific patterns of muscular activation, with peak activations occurring at opposing muscle lengths (contracted or stretched) yet producing similar rates of fatigue. The two methods would be therefore expected to produce similar levels of strength gains, but with differing adaptations along the length-tension relationship curve. Exerting muscles at different lengths produces a shift in peak force, where exercising the muscle at contracted positions shifts peak force towards shorter lengths, while exerting the muscle at stretched positions shifts peak force to longer lengths (Alegre *et al.*, 2014; Brughellli *et al.*, 2010; Brockett *et al.*, 2001; Rassier *et al.*, 1999). These adaptations are consequence of a change in the muscle's architecture: the shift in peak strength to earlier stages of movement is caused by a reduction in the length of the muscle fibres, which renders the muscle slower, weaker at stretched positions and therefore more prone to injury, while muscles that are regularly exerted at stretched positions exhibit longer fibres, which make them faster at contracting, stronger when activated at stretched positions and therefore less prone to injury (Timmins *et al.*, 2016). Establishing whether these outcomes are effectively related to the method of resistance implemented during training, and to the joint position at which the method places the greatest load, would help determine the effectiveness and applicability of elastic resistance in strength training programmes.

The literature presents an abundance of studies on the effects of weight training on different populations, and in different training modalities, while there is still dearth of research on the effects of elastic resistance training on muscle strength adaptations. Elastic training was initially only tested on clinical populations (Aniansson *et al.*, 1984) and is now considered effective for producing strength gains in patients with neck and shoulder pain (Andersen *et al.*, 2011; 2010), in the elderly (Chen *et al.*, 2015; 2013; Yasuda *et al.*, 2014; Aniansson *et al.*, 1984) and in clinical populations (Nyberg *et al.*, 2014; Qi *et al.*, 2014; Ramos *et al*, 2014; Babu *et al.*, 2013; Topp *et al.*, 2002). A few studies have also proven its effectiveness in producing strength gains for healthy populations (Hostler *et al.*, 2001; Behm, 1991) and in producing markers of muscle damage (Aboodarda *et al.*, 2011) and hormonal responses in active males that are pertinent to muscular adaptations and comparable to weight resistance training (Aboodarda *et al.*, 2012).

It has often been suggested that a combination of elastic and weight load would be more effective than using either method on its own, mainly due to their complementary activation patterns as observed in Chapter 6 (Frost *et al.*, 2010; Behm, 1998), although only two publications have so far applied this hypothesis (Bellar *et al.*, 2011; Anderson *et al.*, 2008). They reported that substituting 15-20% percent of the weight load with elastic tension produced significantly greater strength gains in both trained (Anderson *et al.*, 2008) and untrained (Bellar *et al.*, 2011) participants, endorsing the benefits of adding elastic resistance to strength training programmes in order to elicit muscular overload over a wider portion of the range of motion, therefore maximising strength gains. Bellar *et al.* (2011) and Anderson *et al.* (2008) had clearly considered the different muscular activation patterns that elastic resistance produces, and have demonstrated the benefits of increasing time under tension by combining the two resistance methods. However, they only considered increases in 1 repetition maximum (1RM) as a measure of strength adaptation, without accounting for specific changes along the length-tension relationship curve which may have been the precursor of an improved performance in 1RM. The previous chapters of this project have established that combining elastic resistance with free weights increases agonist activation at the end of the concentric phase and increases synergist muscle activation with respect to using weight resistance alone. Therefore, in the Anderson *et al.* (2008) and Bellar *et al.*'s (2011) studies, the combination of the two resistances may have enhanced 1RM gains by recruiting synergist muscles and by inducing greater strength adaptations of the agonist muscle at short lengths. The specificity of these adaptations, however, is not revealed through a comparison of changes in 1RM. Therefore, coupling the analytical observations of muscular activation patterns from the previous chapters with changes in isokinetic and isometric strength can improve the interpretation of any identifiable differences in the adaptations to training with elastic tubes, weights or a combination of the two.

This study, therefore, aimed to identify whether there are differences in isokinetic strength gains and specific changes of isometric strength throughout the range of motion between training with elastic tubes, weights, or a combination of the two.

8.3 Methods

8.3.1 Participants

Twenty-four participants (8 males, 16 females) were recruited for the study, of which 5 (1 male, 4 females) discontinued their participation. The 7 males (age 22 ± 8 years, stature 178 ± 7 cm, mass 76 ± 20 kg) and 12 females (age 26 ± 9 years, stature 162 ± 8 cm, mass 58 ± 12 kg,) who completed the study were either sedentary or lightly active (1 hour of physical activity per week) with no prior resistance training experience. The study was approved by Kingston University Faculty's Ethic committee in line with the declaration of Helsinki.

8.3.2 Resistances

Due to changes in the manufacturer's product, the tubes used for the intervention study had a different external resistance to the ones used in the analytical studies (Section 3.3.2). The Black Thera-band® tubing manufactured in 2016 was used in this study, which is equivalent to 3.3kg of resistance at 100% stretch.

Two strands of the latest Black Thera-band® tubing were used for the elastic training group (T), a dumbbell of 6.6kg was used for the weight training group (W) and the combined condition group (TW) exercised with one strand of black tubing and a dumbbell of 3.3kg in the same hand. Tubes were personalised by reducing their initial length by 10% (see Section 3.3.2) and marking the exact point on which they were to be stepped on (while wearing shoes to ensure proper anchoring). Based on manufacturer's specifications and on 3D motion analysis data gathered from the analytical studies, calculations of external applied loads throughout the range of motion (ROM) are shown in (Table 8.1).

Table 8.1 - Tube resistance equivalents (kg) of Black Thera-band tubing (manufactured after 2015) relative to elbow joint positions, throughout the full ROM of a bicep curl. Calculated based on measured average ROM when training with elastic tubes (n=19).

	START ROM	**90° ELBOW ANGLE**	**END ROM**
WEIGHTS	6.60 kg	6.60 kg	6.60 kg
COMBINED	3.63 kg	6.06 kg	7.41 kg
TUBES	0.66 kg	5.52 kg	8.22 kg

8.3.3 Testing

In the week before training, maximal voluntary isometric strength testing was performed using a Biodex Dynamometer (Biodex Corporation, NY, USA) at internal elbow angles of 150°, 90° and 40° for both limbs. Participants were instructed to perform the intention of flexing the arm at the elbow using maximal force, while receiving loud verbal encouragement. Participants performed the post-test three days after the 8-week training programme was complete. The same dynamometer was used to perform an isokinetic strength test at 120deg·s^{-1} between 170° and 40° internal elbow angle. Three repetitions of concentric-eccentric elbow flexions were performed per limb.

Bicep girth was measured at the muscle belly with a flexed arm and the elbow at 90°. To ensure consistency, the same person measured pre and post girth for all participants and took each measurement three times.

8.3.4 Training

Participants underwent an eight-week home-based training programme of bicep curls. They performed 3 sets of 10 repetitions the first two weeks and increased sets by 5 repetitions every two weeks, finishing with 3 sets of 25 repetitions in the final two weeks of training. The training programme targeted muscular endurance rather than maximal strength. Due to this being a home-based intervention, an increase in repetitions was preferable to an increase in load due to the complexity of the resistance methods that were assigned.

The participants were randomly allocated into one of three training groups: elastic training using tubes only (T), weight training (W) and a combined condition using tubes and weights together (TW). After having performed the baseline strength tests, participants were instructed on how to execute the bicep curls, performed several trial repetitions under the supervision of the researcher to ensure proper technique and received the necessary materials to continue their training at home. They also received a training diary (Appendix B), maintained regular contact with the researcher, by texting on each training day, throughout the intervention to ensure compliance and returned to the laboratory upon completion of their eight-week programme for a post intervention strength test.

8.3.5 Statistical analysis

All data was tested for normality and met parametric assumptions, which were checked using a Shapiro-Wilk test given its recommended use in samples smaller than 30 (Ghasemi & Zahediasl, 2012). A mixed model ANOVA was used to determine significant differences in pre and post training isometric and isokinetic strength between methods. The same statistical analysis was also used to determine within subject differences between dominant and non-dominant limbs, and between elbow angles. A paired t-test was used to find differences between pre and post values within subjects. Significant difference was accepted at alpha level .05.

8.4 Results

Due to study limitations which are elaborated on in the discussion, the following section will comment on the statistical significance of the results and consider visible trends in the data.

8.4.1 Girth

There was no difference in upper arm girth between the three groups either before or after the training programme. Within participants, girth increased significantly (p<.05) for all groups after the eight weeks, with no effect of resistance method between groups (Table 8.2).

*Table 8.2 - Change in girth of the biceps muscles after 8 weeks of biceps curls with tubes, weights or a combination of the two. * Significant difference (p<.05) to Pre value.*

	DOMINANT		**NON-DOMINANT**	
	Pre (cm)	Post (cm)	Pre (cm)	Post (cm)
TUBES (N=6)	28.9 ± 4.8	30.1 ± 4.6*	28.8 ± 5.1	29.3 ± 5.1*
COMBINED (N=7)	29.7 ± 3.1	30.9 ± 2.8*	29.8 ± 3.1	31.1 ± 3.1*
WEIGHTS (N=6)	28.5 ± 2.9	29.5 ± 3.1*	28.3 ± 3.1	29.5 ± 2.8*

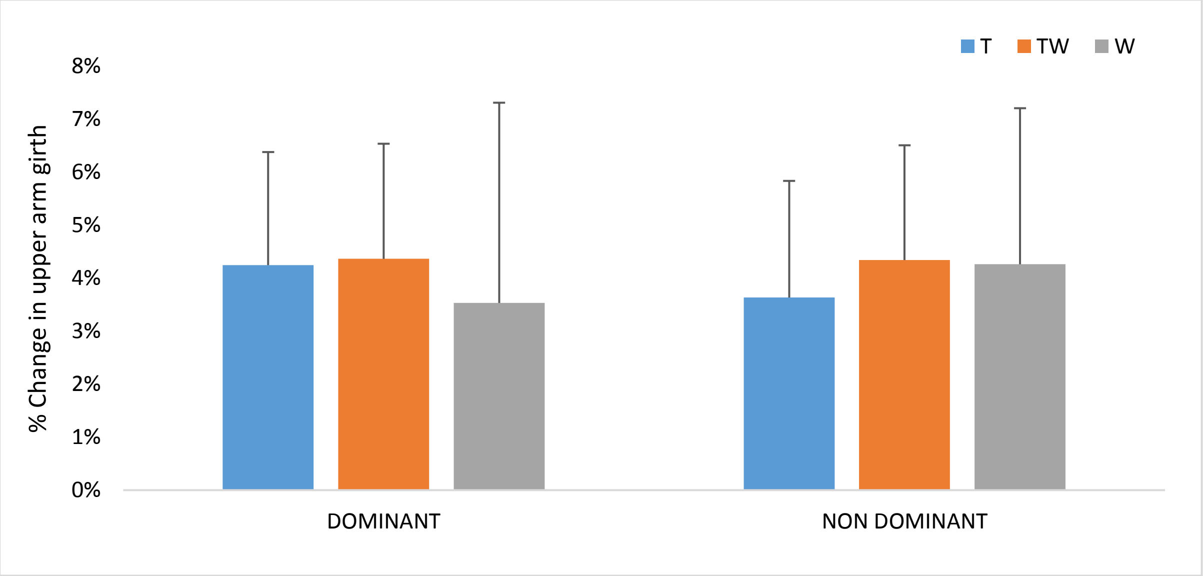


Figure 8.1 - Percentage change in biceps girth after eight weeks of bicep curls for all three training groups (T = Tubes, TW = Combined, W = Weights)

8.4.2 Isokinetic strength

Increases in isokinetic peak torque only reached statistical significance ($p < .05$) for the non-dominant arm in the elastic and weight groups (Table 8.3). There also was a visible tendency (Figure 8.2) for the combined condition to produce the least gains in both limbs and for the elastic condition to produce the greatest gains. Peak torque tended to occur at greater elbow angles in all conditions post intervention (Table 8.4), with greater differences in the weight condition, and lesser differences in the combined condition, but results were not statistically significant.

Table 8.3 - Isokinetic peak torque of the dominant and non-dominant arms for the three training groups, made before and after the eight week training programme. Significant difference (p<.05) from pre value.*

	DOMINANT		**NON-DOMINANT**	
	Pre (Nm)	Post (Nm)	Pre (Nm)	Post (Nm)
TUBES (N=4)	18.70 ± 12.07	30.98 ± 10.99	17.03 ± 9.34	30.55 ± 11.70*
COMBINED (N=6)	22.24 ± 7.32	26.26 ± 10.55	22.56 ± 4.72	27.58 ± 10.22
WEIGHTS (N=5)	19.38 ± 13.98	26.63 ± 6.51	18.87 ± 11.09	28.83 ± 7.38*

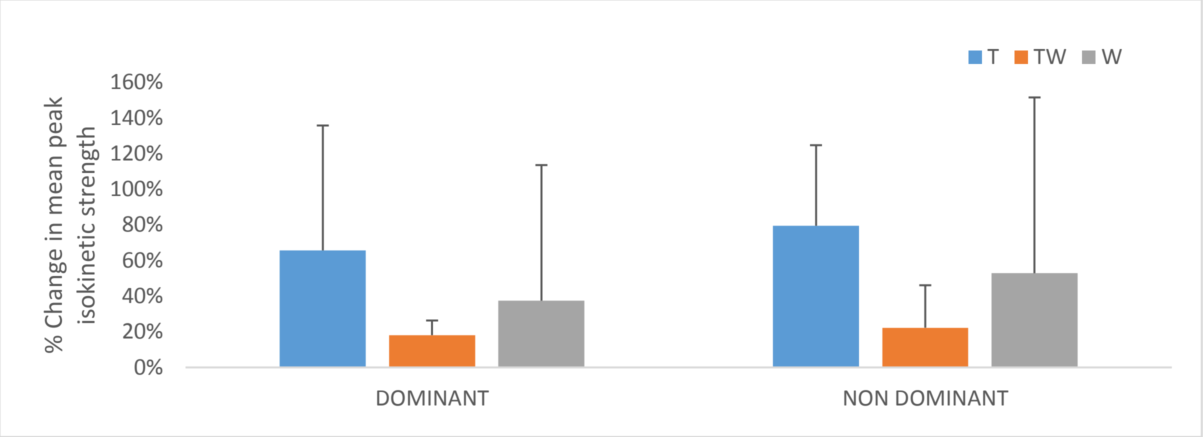


*Figure 8.2 - Percentage change in isokinetic torque of the dominant and non-dominant arms for the three training groups (T = Tubes, TW = Combined, W = Weights) after the eight week training programme. *Significant increase in torque.*

Table 8.4 - Elbow angles at which peak torque occurred during the isokinetic test at 120deg·s^{-1}.

	DOMINANT		**NON-DOMINANT**	
	CONCENTRIC			
	Pre	Post	Pre	Post
TUBES	124° ± 50	140° ± 28	126° ± 51	147° ± 21
COMBINED	111° ± 43	119° ± 35	121° ± 40	126° ± 27
WEIGHTS	88° ± 42	125° ± 39	120° ± 47	137° ± 24
	ECCENTRIC			
	Pre	Post	Pre	Post
TUBES	92° ± 57	90° ± 37	123° ± 44	128° ± 28
COMBINED	79° ± 22	91° ± 43	87° ± 36	84° ± 40
WEIGHTS	60° ± 45	76° ± 33	79° ± 53	93° ± 50

8.4.3 Isometric strength

8.4.3.1 Within subject effects

Increases in isometric strength were significant for both the dominant and non-dominant arms at 150° (D: p=.001; ND: p=.026) and at 40° (D: p<.001; ND: p<0.01) for all groups, but not at 90°. Within subjects, isometric strength gains differed between elbow angles (D: p=.005; ND: p<.001), where the T and TW groups obtained the greatest gains at 40° and the W group at 150°; all groups obtained the lowest gains at 90° (Figure 8.3, Figure 8.4).

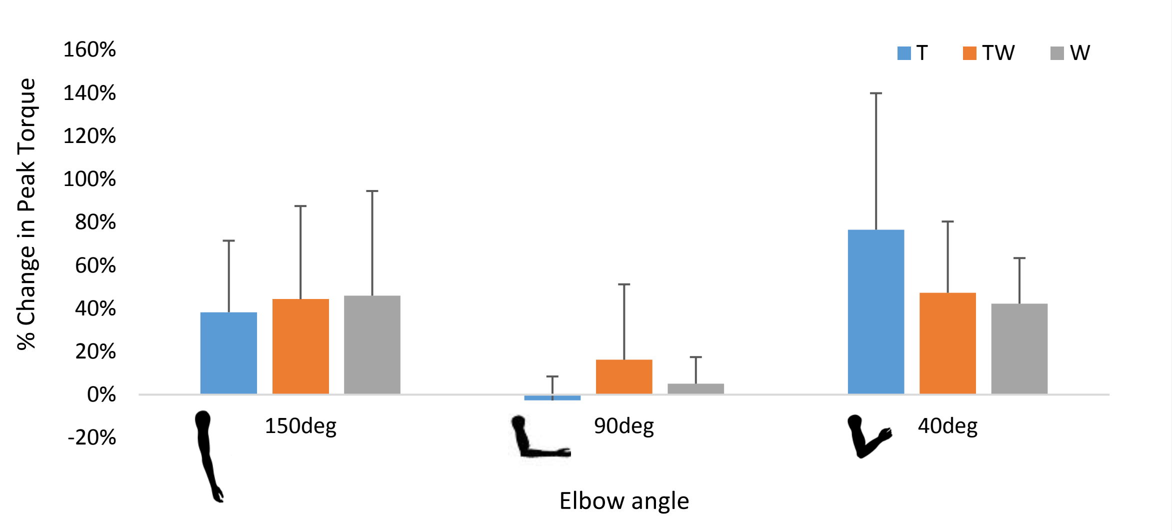


Figure 8.3 - Change in isometric torque output of the dominant arm (D) at three different elbow angles after eight weeks of biceps curls with elastic resistance (T), weights (W) or a combination of the two (TW).

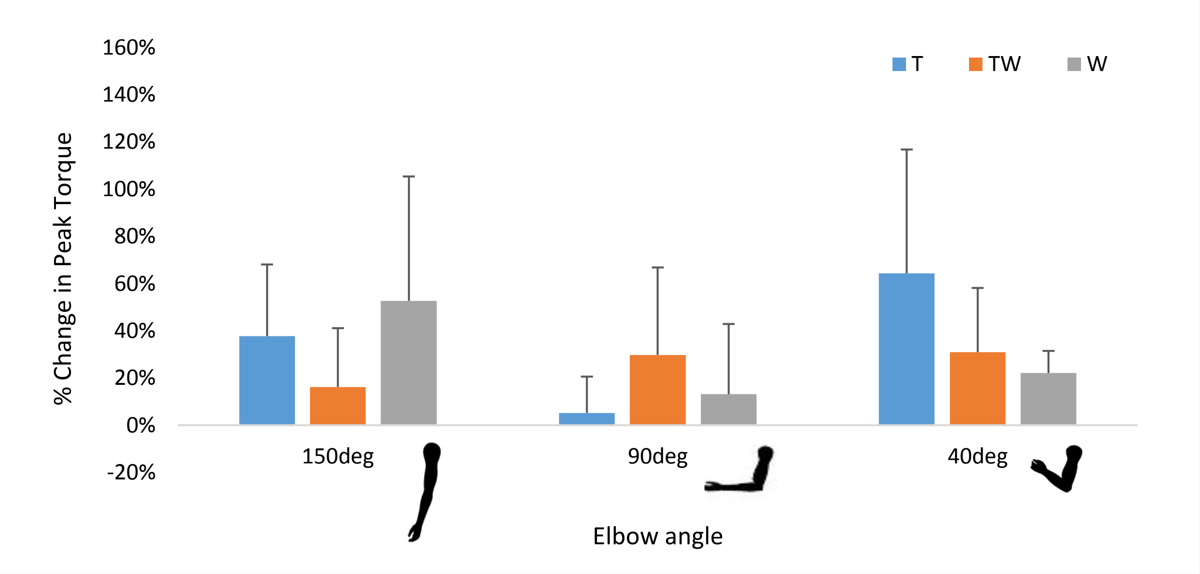


Figure 8.4 - Change in isometric torque output of the non-dominant arm (ND) at three different elbow angles after eight weeks of biceps curls with tubes (T), weights (W) or a combination of the two (TW).

8.4.3.2 Between subject effects

Differences in pre and post isometric strength were not statistically significant between groups at any of the three elbow angles. Effect size and observed power were, however, extremely low due to the small samples used in the study (Partial Eta^2≤ .002; Observed power ≤.052).

Table 8.5 – Isometric strength recordings of the dominant and non-dominant arms for the three training groups, at three different internal elbow angles (150°,90°,40°) , made before and after the eight week training programme.

ROM	GROUP	DOMINANT		NON-DOMINANT	
		Pre (Nm)	Post (Nm)	Pre (Nm)	Post (Nm)
150° 	**TUBES (N=6)**	28.58 ± 21.53	33.15 ± 19.80	27.38 ± 20.80	30.80 ± 16.45
	COMBINED (N=7)	25.28 ± 12.02	32.88 ± 7.47	30.15 ± 12.85	32.73 ± 10.94
	WEIGHTS (N=6)	26.19 ± 14.52	35.09 ± 17.68	29.11 ± 15.35	39.09 ± 18.17
90° 	**TUBES (N=6)**	36.22 ± 19.77	35.10 ± 18.60	35.18 ± 19.24	35.12 ± 16.91
	COMBINED (N=7)	28.65 ± 8.08	31.58 ± 7.28	28.82 ± 10.72	34.33 ± 5.87
	WEIGHTS (N=6)	33.19 ± 13.76	35.13 ± 16.96	33.24 ± 14.29	35.36 ± 14.82
40° 	**TUBES (N=6)**	18.73 ± 11.64	24.85 ± 6.86	20.58 ± 11.15	28.10 ± 9.27
	COMBINED (N=7)	21.52 ± 7.23	30.67 ± 8.10	23.47 ± 9.26	29.02 ± 7.74
	WEIGHTS (N=6)	17.14 ± 5.75	23.87 ± 6.83	20.34 ± 7.52	24.53 ± 8.04

8.5 Discussion

All three resistance methods implemented in this training intervention produced significant gains ($p<.05$) in isometric strength at varying muscle lengths, which reflected the muscular activation patterns reported in previous chapters of this thesis, while only T and W exhibited significant increases in isokinetic strength.

8.5.1 Hypertrophy

Increases in girth were statistically significant after eight weeks of training in all groups and did not differ between conditions, indicating that there was no effect of resistance method on hypertrophy at low to moderate intensity, although it is hard to speculate what may happen with greater loads. If, by exerting the muscles at different lengths, elastic resistance did produce a decrease in the number of sarcomeres, and weights produced an increase thereof, then a training programme of longer duration, with a focus on strength development by implementing greater loads and less repetitions, might induce greater increases in girth with weights.

The changes observed in this study reflect the lower range of expected hypertrophy reported by previous studies, where strength training at loads close to 50% 1RM are expected to produce hypertrophic gains of 5-25% (Fry *et al.*, 2004) and are usually only observed after the first 8 weeks of training (Knight and Kamen, 2001). In addition, it was reported that low intensity training (40% 1RM) of a full weight training circuit does not provide sufficient stimulus to produce hormonal anabolic responses (Rubin *et al.*, 1999 in Fry *et al.*, 2004). Therefore, considering that the programme used in this study involved sessions of an average duration of 5 minutes, 3 times a week, in addition to being of low intensity, the minimal hypertrophic changes are not surprising. Greater loads and longer training sessions would have induced greater adaptations and would have possibly provided better insight on the effect of these resistance methods on hypertrophy.

8.5.2 Isokinetic strength

Elastic and weight resistance produced similar increases of isokinetic strength in both arms, although results were only significant for the non-dominant arm; increases were not significant in the combined condition for either arm. The similar gains in the elastic and weight training groups reflect findings of similar peak activation reported in Chapter 4 and similar rates of fatigue in Chapter 7 of this project. Initial strength adaptations in untrained individuals have been attributed to an improved central neural drive rather than hypertrophic changes (Hakkinen, 1989). Therefore, considering that fatigue plays a determining role in muscle strength adaptations and that elastic and weight resistance of comparative loads produce equal biceps peak activation (Chapters 4, 5, 6) and equal rates of fatigue (Chapter 7), the similar increases in isokinetic strength are unsurprising. Furthermore, the significant yet low increases in girth (4%) demonstrate that, although hypertrophic changes did occur, an improved neural drive might have been the greater contributor to increases in isokinetic strength in this study. Considering that the elastic condition recruits secondary muscles more than weight resistance (Chapters 4, 5, 6), the gains could be attributed to greater adaptations in secondary muscles which may have contributed to a greater torque output. In contrast, the increased isokinetic torque in the weight condition may be attributed to the angular specificity of the application of load. Isometric strength tests demonstrated a connection between greater muscular activation at the beginning of the ROM (Chapters 4, 5) and greater strength gains at those same positions in the weight condition, especially in the non-dominant arm (Figure 8.4). The direct connection between the specificity of muscular activation patterns, isometric and isokinetic strength adaptations lies in the fact that isokinetic strength is dependent on the strength output generated at early stages of movement, where a greater early strength output generates the necessary momentum to bring the limb throughout the range of motion, as demonstrated in Chapter 5. Based on the findings in muscular activation patterns reported in previous chapters of this thesis, and on the significant increases in isokinetic torque observed in this study, it is suggested that elastic and weight resistance may produce strength gains through slightly different mechanisms. Following dynamic exercise, weight training may produce increases in isokinetic strength primarily due to its application of load at early phases of ROM where agonist muscles are stretched, hence provoking an increase of in-series sarcomeres, making this method more appropriate for lifting and power training. In contrast, elastic training may increase strength by improving agonist-synergist co-activation, making it more appropriate for improving motion control and stability during dynamic movements. Measuring changes in 1RM would have provided some more insight into the contribution of other muscles on overall performance, giving ecological validity to the results. This was not considered when designing the study and therefore poses a limitation for the discussion of the results.

The lower gains in isokinetic strength in the combined condition were a surprising finding, especially considering that both Bellar *et al.* (2011) and Anderson *et al.* (2008) found that substituting only 15% and 20% of weight resistance with elastic tension was sufficient to increase 1RM more than with weight training alone. The findings reported in this study may be explained by the muscular activation patterns observed in Chapter 6. Although absolute peak activation was not significantly different across the different conditions (Figure 6.2), the muscular activation patterns clearly show that the peak activations elicited by the weights at the beginning of the ROM, and the ones elicited by tubes at the end of the ROM, were both higher than the values observed in the combined condition (Figure 6.3). This indicates that, despite time under tension being longer in the combined condition, the amplitude of activation remains lower than when using one of the conditions on their own. Therefore, peak activation seems to have been the determining factor in producing strength gains in this study. Considering that both time under tension and load volume influence strength adaptations (Tran *et al.*, 2006), a greater proportion of each load, the specific value of which could be investigated through further research, could still provide the necessary stimulus to maximise muscle overload throughout the ROM.

Nonetheless, these findings still present a strong contradiction with those of Anderson *et al.* (2008) and Bellar *et al.* (2008), who both reported significantly greater gains in 1RM when substituting only

15-20% of the load with elastic tension during squats and bench presses. Considering that the loading strategy implemented in this study targeted muscle endurance rather than maximal strength, the differences in strength gains are unsurprising. However, another factor that may have influenced these differences may lie in the choice of exercise. Both bench presses and squats involve the movement of two joints and require a much larger number of muscles than do bicep curls, which only involve one joint. Considering that, as established in Chapter 6, the combination of elastic and weight resistance engages auxiliary muscles significantly more than weight resistance alone, the greater gains in 1RM reported by the two publications may be connected to an improved recruitment of synergist and auxiliary muscles in the combined resistance group which, working in unison, may have achieved the improved 1RM performance. The bicep curl, however, relies heavily on the biceps brachii as the primary mover, with a relatively small contribution of the synergist muscle (brachialis), whose activation could not be detected with surface EMG, and any adaptations of which would have had a lower impact on total force output with respect to compound exercises such as the bench press due to the different number of muscles involved. These observations reiterate the difficulty in standardizing and comparing a variable resistance such as the elastic one, giving way for a vast area of research on the applicability of elastic resistance training for a variety of exercises and disciplines.

8.5.3 Isometric strength: from activation patterns to strength adaptations

Having substantiated that, during bicep curls, elastic resistance elicits a greater muscular activation at acute elbow angles and a lower activation than weights at obtuse elbow angles (Chapters 4, 5), it is expected that the adaptations to elastic training would also differ from those to weight training. Despite these differences, in a meta-analysis on elastic training, Aboodarda *et al.* (2016) argued that, when the limb moves throughout the entirety of the ROM, total EMG activation levels off, offering a generic muscular activation that is equal in both the elastic and weight conditions and would therefore produce similar strength adaptations. Given that peak and total biceps activation were equivalent in both methods (Chapter 5), and that initial strength gains are attributed primarily to an increase in central neural drive regardless of joint angle, rather than hypertrophic adaptations (Hakkinen, 1989), Aboodarda *et al.*'s, (2016) suggestion may prove true at initial stages of strength training. It may also be worth noting that the increases in strength differed slightly between the weight and elastic conditions and, although these changes did not reach significant differences, a longer intervention with greater loads might be sufficient to promote changes in isometric force production at opposing muscle lengths. Should this theory prove to be accurate, it would indicate effect of resistance method on muscle contractile properties, reinforcing the importance of considering angle specificity when comparing methods of resistance.

Increases in strength tended to be lowest at an elbow angle of 90° across conditions. Biomechanical studies have established that the biceps moment arm is at its most advantageous length when the elbow joint is flexed at about 90° (Murray *et al.*, 1995; Zuylen *et al.*, 1988) and that, due to optimal filament overlap, biceps force generating capacity is greatest at this position, it is not surprising that the muscle would also experience a diminished strength gain compared to the other two, less advantageous positions (150°, 40°). Furthermore, these findings are not novel; studies on the knee extensors following dynamic strength training reported significantly lower gains in isometric strength at 90° knee angles compared to increases in dynamic strength (Baker *et al.*, 1994; Thorstensson *et al.*, 1976), and one particular study found no improvement in isometric strength despite significant improvements in weight lifting performance and hypertrophic gains (Sale *et al.*, 1992). It was concluded that increases in strength are specific to the modality of training, and that measures in isometric strength are not an appropriate method for testing improvements in performance. The aforementioned studies, however, only considered one specific knee angle (90°) where the knee extensors are close to their most advantageous point (75°). The data reported in this study conveys a different picture of the effects of dynamic training on isometric strength, where significant gains were observed at obtuse and acute joint angles, suggesting that improvements in dynamic strength may be in part mediated by an improvement in contractile properties at less advantageous muscle lengths. Other factors that may contribute to increases in strength gains include the synchronisation of agonist-synergist muscle recruitment (Cormie *et al.*, 2011; Behm, 1995) and increased strength in synergist and stabilizer muscles. The investigation of these factors is beyond the scope of this study, however the observations reported in Chapters 4, 5 and 6 of this project indicate a variability in the contribution of synergist muscles to different resistance methods, which may effectively transfer to improvements in performance.

Of note was the observed greater improvement in strength at 90° in the TW group compared to the T and W groups. Calculations of external applied load at 90° show that the combined condition provided a lighter load than the free weights, ruling out the possibility that a greater force may have produced the differences in strength gains at this angle. An explanation to this difference may therefore lie in the different activation patterns elicited by the three resistance methods. While tubes and weights would have elicited peak activations at opposing phases of movement (90° and 50° elbow angles respectively at 120deg·s^{-1}), combining the two resistances produced a plateau of muscular activation throughout the concentric phase of the bicep curl that covered all elbow angles between 110° – 50° (Section 6.4.1). Given that, at equal loads, a greater time under tension produces greater gains (Burd *et al.*, 2012; Tran *et al.*, 2006), the greater increases in isometric strength at 90° elbow angle may be attributed to the plateau of activation generated by the combined condition at mid ROM.

As for intra-subject responses, although trends for the T and W groups remained consistent with the dominant and non-dominant arms, the TW group exhibited mixed responses between limbs, with increases that averaged those of the other two conditions in the dominant arm, but with no apparent trends in the non-dominant arm. This may be attributed to the variable load of the combined condition in association with a lower strength and neuromuscular coordination in the non-dominant limb. Previous chapters have discussed the unpredictability of elastic resistance, that changes in both magnitude and direction throughout the ROM; in addition, the combination of elastic and weight resistance was described as "confusing" by participants due to an expectation of the load to behave as a weight, combined with the addition of an unanticipated elastic force pulling in different directions as ROM progressed. This unpredictability may have affected technique and consistency in the training of the non-dominant arm, affecting strength adaptations. These findings reflect those of previous studies that reported a significant increase in strength following strength and power training programmes using a combination of elastic and weight resistance compared to free weights only (Bellar *et al.*, 2011; Anderson *et al.*, 2008), attributing the difference to the variable resistance that elastic tension offers, eliciting an increased muscular overload at joint angles that are normally more advantageous with weight resistance.

8.5.4 Length tension relationship – applicability and implications

It has so far been established that long term strength training that focuses muscular exertion at short muscle lengths has been found to decrease the number of in-series sarcomeres per fibre, while the opposite is true for exerting muscles at long muscle lengths (Brughellli *et al.*, 2010; Rassier *et al.*, 1999). Consequently, strength training that focuses exertion at long muscle lengths causes a shift in peak torque towards longer muscle lengths (Alegre *et al.*, 2014; Brockett *et al.*, 2001), and likewise for short muscle lengths (Rassier *et al.*, 1999). These adaptations affect the muscle’s behaviour along the length-tension relationship curve, rendering it stronger, or weaker, at different stages of contraction, and consequently making it more, or less, prone to injury (Timminis *et al.*, 2016). As previously mentioned, the findings reported in this project suggest that the differences in muscular activation patterns elicited by the elastic and weight resistance could produce changes in muscle architecture following an longer intervention with greater loads, resulting in shifts of force generating capacity along the length-tension relationship curve. Further studies are needed to confirm this suggestion which, if proved correct, would affect both performance and injury risk and should therefore be considered with caution.

Elastic training has often been implemented in rehabilitation training thanks to the gradually increasing resistance that it provides (Andersen *et al.*, 2010), however, it has not yet been considered whether implementing this method of resistance would affect changes in muscle architecture. Although injured muscles clearly benefit from the gradual application of load throughout the ROM, as opposed to abrupt changes in activation often elicited by weight resistance, healed muscles are also characterised by shorter fibres which render them weak on the descending limb of the length-tension relationship, making them prone to further injury (Timmins *et al.*, 2015). Previous studies have in fact suggested training muscles at long lengths in order to increase fibre length, hence reducing injury risk (Proske *et al.*, 2007). Although the benefits of elastic training for initial stages of rehabilitation are undisputable, this study suggests that long term elastic resistance training may further reduce the length of muscle fibres, therefore, as the strength programme progresses the inclusion of other resistance methods would be advisable in order to produce muscular overload at stretched muscle lengths, with the aim of increasing sarcomere number and fibre length.

In performance contexts, however, some athletes may benefit from an increase in strength at latter stages of ROM and may therefore consider the application of elastic resistance for sport-specific training. Examples of this include impact sports, where movements are usually performed with little or no resistance, suddenly encountering a high resistance at the end of the movement. This may include martial arts, tennis and baseball (ball impact), where the athlete is expected to follow through with the movement despite a sudden increase in resistance at impact. Applying elastic resistance to sport specific movements may help mimic these characteristics, producing strength adaptations at desired phases of movement. Further studies are, however, needed to confirm this suggestion.

8.5.5 Study limitations

Due to the small sample size of this study, much of the data appeared to show trends, but did not reach statistical significance. It could simply be that, despite the evident difference in activation patterns produced by the two resistance methods, these differences were not sufficiently prominent to produce distinguished strength adaptations; however, the low effect size and observed power reported from the statistical analysis suggest that a number of factors, including study design and participant compliance, may have affected the results.

Primarily, a small sample size was used in this study, which was not homogenous in gender or initial strength. In order to minimise variance, an equal number of males and females were allocated to each training method, and participants were matched by initial strength before being assigned to a group. In some studies, gender has not been found to affect results in strength interventions to the point of discounting statistical significance, where men and women exhibited similar proportional strength and muscle mass increases (Blazevich *et al.*, 2003; Abe *et al.*, 2000), although other studies report that women gain significantly higher proportions of strength following elbow flexor strength training (Visich *et al.*, 2003). In addition, the reduced number of participants and the lack of homogeneity in initial strength would have produced mixed results, which are reflected in the small effect size and high standard deviations. A larger, and more homogenous, participant sample would have reduced the risk of committing a type II statistical error.

Having implemented a home-based intervention design also meant that, despite giving participants clear instructions on movement execution, numerous variables could not be directly controlled, where differences in technique, velocity and compliance may have substantially affected adaptations between individuals. In previous findings of this project, action velocity was seen to substantially affect patterns in muscular activation (Chapter 5), where higher velocities exhibited more prominent differences in muscular activation at the beginning and end of the ROM between conditions (Section 5.5.1). Given that pilot testing demonstrated an average self-paced movement velocity of 120deg·s^{-1} with a high inter-individual variability (Section 3.3.1), it could be speculated that participants who exercised with higher movement velocities would have promoted strength adaptations at specific joint angles that reflected the opposing muscular activations observed in Chapters 5 & 6, while participants exercising with slow movements would have obtained a more homogenous distribution of strength across the ROM, and of lower proportion.

Another crucial aspect of exercise that cannot be monitored during home-based interventions is technique. In Chapter 4, bicep curl technique was also found to affect patterns in muscular activation in the elastic condition, where participants who lifted the elbow at the end of the ROM exhibited higher peaks in biceps activation than those who did not. A reflection of this is observed in this chapter through the difference in adaptations observed between the dominant and non-dominant arms, which portrayed similar strength gains at 150° and 90°, but not at 40°. The non-dominant arm may not have been strong enough to complete full ROM, resulting in lower ($p=.02$) strength gains at acute elbow angles (40°). The ability to complete full ROM with 10 repetitions was checked at the beginning of the intervention; if participants did not comply with all training sessions in the home-based intervention they may have found difficulty in completing the movement with the non-dominant arm once repetitions were increased. This is would not surprising, since novices often exhibit strength imbalances between dominant and non-dominant limbs, which can affect performance (Table 8.5).

Lastly, given that significant strength adaptations are most often observed after 4-8 weeks with 60% 1RM in novices (Kraemer and Ratamess, 2004), and are mostly attributed to neural rather than sarcomeric adaptations (Bellar *et al.*, 2011; van Cutsem *et al*, 1998; Hakkinen and Komi 1983), it could be argued that the duration of the intervention may not have been sufficiently long to produce substantial changes to the muscles' architecture. It has, however, been demonstrated that a training period of 5-8 weeks is sufficient to produce structural adaptations in the muscle fibres (Blazevich *et al.*, 2003) resulting in a shift of peak torque to different joint angles (Alegre *et al.*, 2014). Considering those findings, and the trends observed in this study, it is plausible to suggest that 8 weeks of bicep curls at low to moderate intensity were sufficient to prompt some architectural changes in novices, moderately affecting the force generating capacity at different muscle lengths. Further studies may consider investigating the effect of resistance method on fibre length and strength adaptations at different muscle lengths with greater loads, different exercises and a longer training duration.

Considering that a home-based intervention provides external validity by giving a better reflection of real life scenarios, where many individuals exercise without thorough instructions or monitoring, the variability of the results arguably reflects the array of adaptations that novice populations would obtain with minimal instruction and further underlines the importance of selecting appropriate resistance methods, velocities, loads and ROM when training for performance.

8.5.6 Conclusion

In conclusion, the different muscular activation patterns observed under elastic and weight resistances, and the combination thereof, were reflected in the angular specificity of isometric strength adaptations following dynamic strength training. While isokinetic strength gains were similar between the elastic and weight conditions, elastic training was more effective at increasing isometric strength at contracted muscle lengths, while weight resistance produced greater strength gains at stretched muscle lengths, suggesting an effect of resistance method on architectural adaptations of the muscle fibres. The combined condition produced overall lower strength gains with respect to the other methods, with slightly greater isometric gains at 90° elbow angle, suggesting that load proportions greater than those implemented in this study may effectively maximise muscle overload throughout the range of motion. Further studies should implement greater loads, over longer periods, with all three methods and further investigate these effects on compound exercises. Further research may also consider directly investigating the impact of elastic and weight resistance on muscle fibre structure.

Chapter 9

Project Summary

9.1 Summary

The aim of this project was to provide an understanding of muscular responses elicited by elastic resistance exercise, of how these differ to free weight training and in what way these differences could impact long term strength adaptations.

The literature currently presents a great variability in findings, with little congruity among studies: the collective evidence of electromyographic (EMG) studies on elastic training is not yet cohesive on whether auxiliary muscle engagement, muscle recruitment and magnitude of concentric and eccentric muscle activation differ between elastic and weight resistance methods. In addition, most studies reported their findings in terms of peak and mean EMG, which lack the necessary detail to pinpoint specific differences in activation patterns throughout the range of motion (ROM), and which would enable a more comprehensive comparison with other methods of resistance. A more comprehensive understanding of muscular responses through both spectral analysis and intervention studies would enable a prediction of biomechanical outcomes of their use in long term training programmes.

In taking an analytical approach to the investigation, the first study (Chapter 4) laid out a base for the understanding of how muscular activation changes throughout the ROM during four exercises that are commonly implemented in strength and rehabilitation (bicep curl, lateral raise, leg extension, leg curl). The study confirmed that, as indicated by Aboodarda *et al.* (2011), the increased resistance caused by a reduction in the initial length of the elastic tube results in a significant increase of total and peak muscular activation of all muscles involved, without affecting the patterns of muscular activation throughout the ROM. In contrast, however, Abbodarda *et al.* (2011) reported that adding multiple tubes in parallel increased muscular activation at the beginning of the ROM without causing significant increases in peak activation, thus offering a less variable activation curve throughout the ROM. An analysis of secondary muscle activation revealed that these were consistently more active with elastic resistance than with weights, confirming the findings of several studies that also reported a higher activation of synergist, core and stabilizer muscles with elastic resistance (Vinstrup *et al.*, 2015; Sundstrup *et al.*, 2014; Jakobsen *et al.*, 2014; Lister *et al.*, 2007) and contradicting those who reported no difference in secondary muscle activation between conditions (Serner *et al.*, 2014; Brandt *et al.*, 2013; Sundstrup *et al.*, 2012; Witt *et al.*, 2011; Matheson *et al.*, 2001). There was a tendency for secondary muscles to be more active with elastic resistance than with weights (Brandt *et al.*, 2013; Matheson *et al.*, 2001). Finally, through the analysis of the muscular activation patterns of both primary and secondary muscles throughout the ROM, the first study provided conclusive evidence that, in exercises where the direction of the elastic tension is parallel to the line of gravity, elastic resistance provokes opposing muscular activation patterns to weight resistance, where as one increases the other decreases.

The second study (Chapter 5) investigated the effect of movement velocity on the mentioned muscular activation patterns. The differences in muscular activation patterns observed in the first study became more pronounced at higher velocities, where peak activation shifted towards initial stages of movement with weight resistance while it remained at latter stages of movement with elastic resistance. Previous publications had already recognised that, during high speed weight resistance exercise, peak activation increases and occurs earlier in the ROM (Knight & Kamen, 2001; Van Cutsem *et al.*, 1998). In addition to confirming these findings, Study 2 established that peak activation also increases at higher velocities with elastic resistance but it always occurs at the end of the ROM, independent of movement velocity. These findings suggest that the two methods would produce differing architectural adaptations if implemented in long term strength training programmes, where elastic resistance would be more likely than weight resistance to cause a reduction in the length of the muscle fibres (Brughellli *et al.*, 2010; Rassier *et al.*, 1999), hence shifting peak strength output to shorter muscle lengths and potentially rendering the muscle more prone to injury (Timmins *et al.*, 2016). Study 2 also confirmed that synergist muscles continue to be more active with elastic resistance, portraying a more marked difference at high movement velocities, determining that this method may be more effective than weights at improving proprioception and joint stability, especially during high speed training.

This information is especially valuable for professionals in both performance and rehabilitation settings. Elastic training, due to its gradual increase in resistance throughout the ROM, even at high velocities, appears to be more appropriate than weight resistance at initial stages of rehabilitation where healing muscles are susceptible to abrupt changes in load. As muscular rehabilitation programmes progress, elastic resistance becomes a valuable form of training due to its greater engagement of auxiliary muscles, promoting joint stability and reducing further risk of injury. However, given that elastic resistance elicits peak activation at the end of the movement, where the agonist muscle is contracted, its exclusive use could be counterproductive for long term strength programmes. The resulting shortening of the muscle fibres that occurs when exerting muscles at contracted positions is detrimental to the muscle’s architectural composition and should therefore be compensated by using weights and high movement velocities; this would exert the muscle at stretched positions, hence prompting a lengthening of the muscle fibres and reducing the risk of further injury. In addition, as initially speculated by Behm (1991), the findings suggest that elastic resistance could be effectively implemented in performance contexts by combining it with weight resistance during power training to ensure muscular overload throughout the entire movement, therefore maximising strength gains.

Despite numerous speculations that the combination of the two methods would effectively exert the agonist muscle throughout the entire ROM (Frost *et al.*, 2010; Wallace *et al.*, 2006; Behm *et al.*, 1991), no evidence of this had yet been reported in the literature. Therefore, considering the substantial differences observed in the muscular activation patterns of the two resistance methods, the third study (Chapter 6) aimed to confirm speculations of their complementary nature by combining elastic and weight resistance in the same repetition. When participants held both a dumbbell and an elastic tube in the same hand during bicep curls, the patterns of agonist activation displayed a plateau of muscle activity throughout the concentric phase that comprised all joint angles from where peak activation occurred with weight resistance to where it occurred with elastic resistance. Secondary muscles, on the other hand, were more engaged with the combined resistance than with weights, closely reflecting the patterns and magnitudes observed with elastic resistance alone. The findings in Study 3, therefore, confirmed that by combining half weight resistance with half elastic tension produces magnitudes and patterns of muscular activation that reflect a combination of the two resistance methods, while providing the added benefit of engaging secondary muscles more than with weight resistance alone.

The fourth study (Chapter 7) examined the rate of fatigue during elastic and weight resistance exercise through spectral analysis of EMG readings, concluding that, at comparative loads, elastic and weight resistance elicit similar rates of fatigue of the agonist muscles. When related to the previous studies, these findings indicate that rate of fatigue is affected by peak and total activation, independently of where the peak occurs along the ROM. Considering that fatigue plays an important role in muscle strength adaptations, this also suggests that maximal isokinetic strength may increase at similar rates in strength programmes implementing either resistance method.

Finally, an intervention study (Chapter 8) was implemented to confirm the numerous speculations made from the analytical studies. The first two studies inferred that elastic and weight resistance would produce strength adaptations at different muscle lengths eliciting peak activation at opposing phases of ROM; the third study suggested that by combining the two resistance methods strength gains would be uniform throughout the ROM due to a longer activation curve in the concentric phase; and the fourth study confirmed that elastic and weight resistances of comparative loads elicited equal rates of fatigue, further suggesting equal effectiveness in producing strength adaptations. The intervention study found evidence of specificity in strength adaptations along the length-tension relationship curve, where elastic resistance produced greater isometric strength gains than weight resistance at short muscle lengths, weight resistance produced greater gains than elastic resistance at stretched muscle lengths, and the combined condition produced greater gains than the two methods alone at mid ROM. These findings demonstrate a synergy between muscular activation patterns and strength adaptations, alluding to a change in muscle fibre architecture following the intervention.

9.2 Applications

The following sections offer an attempt to determine the efficacy and applicability of elastic resistance for various aspects of resistance training, basing each statement on findings gathered during this project. A summary of the mentioned proposed methods is displayed at the end of the section in Table 9.1. The table is neither exhaustive nor exclusive, but simply offers a suggestion based on the evidence contained in this thesis and other recent publications (Bellar et al., 2011; ACSM, 2009; Rhea et al., 2009; Anderson et al., 2008).

9.2.1 Physiotherapy and rehabilitation

The most explicit characteristic of elastic resistance is the property of the material which offers a progressive load with its elongation. This has rendered the material very attractive for rehabilitation settings where low, gradually increasing loads are considered beneficial for individuals suffering from a muscular injury or musculoskeletal condition (Andersen *et al.*, 2011). The findings from this thesis confirm that elastic materials place the greatest exertion at the end of the ROM (Chapter 4), regardless of movement velocity (Chapter 5), making this material ideal for ensuring the safe execution of an exercise. By placing load at the end of the ROM, elastic resistance exerts the agonist muscles when they are shortened and, therefore, at a stronger and more advantageous filament overlap (Rassier *et al.*, 1999) reducing the risk of injury. The gradual increase in load throughout the movement also enables the individual to have control over the exercise by being able to predict any excessive increases in resistance, hence avoiding abrupt changes in load which could exacerbate the injury. Furthermore, recovering patients may benefit from the neurological adaptations that are provided by high speed training, such as an increased motor unit firing frequency and motor unit synchronisation (Knight and Kamen, 2001; van Cutsem *et al.*, 1998). Therefore, provided that elastic tubes retain their gradual application of force even at high strain rates (Patterson *et al.*, 2001), elastic resistance would enable the implementation of resisted high speed training for neuromuscular rehabilitation, promoting high accelerations without sudden increases in load. Thus, ensuring the preservation of musculoskeletal health is imperative to rehabilitation settings, and the gradual load offered by elastic resistance appears ideal for such situations.

9.2.2 Strength rehabilitation

As the rehabilitation programme progresses, the elastic resistance may be increased by either shortening the initial length of the elastic tube or by adding several tubes in parallel. While the former increases peak activation without significant changes at initial stages of movement (Chapter 4), combining several shortened tubes in parallel increases initial activation without significant changes in peak activation at the end of the concentric phase (Aboodarda *et al.*, 2001). Therefore, shortening stiffer tubes increases peak muscle activation at the end of the ROM, ensuring that muscular exertion is retained only at short muscle lengths (Chapter 4), while adding lighter tubes in parallel should increase muscle activation at initial phases of movement with a lesser effect on peak activation (Aboodarda *et al.*, 2001), offering a longer time under tension and placing some resistance at stretched muscle positions. Both methods will still ensure a gradual application of load throughout the movement, reaching maximal exertion at contracted muscle lengths, hence providing a safe application of resistance for muscles that may still be susceptible to injury.

A further progression in strength rehabilitation may then include the combination of elastic and weight resistance in the same repetition. As discussed in Chapter 6, the combination of the two resistance methods offers a wider muscle activation curve, including high levels of activation throughout most of the ROM rather than a peak activation at a specific muscle length. This increases time under tension and offers muscular exertion at all muscle lengths, hence promoting adaptations throughout the entire ROM. Alternative resistance methods that offer a similar activation curve to the one described include dynamometers and some gym machines (Aboodarda *et al.*, 2011), however, combining elastic and weight resistance still offers the added benefit of engaging auxiliary muscles more than with weights or gym machines (Chapter 6), aiding in the stabilization of joints during injury rehabilitation or prevention. Therefore, the use of elastic resistance, either on its own or in combination with weights, can promote strength adaptations in the agonist muscles with a safer application of load in comparison to weight resistance, and offers the added benefit of engaging auxiliary muscles.

Due to the variability in both the direction and the magnitude of its applied load throughout the ROM, elastic resistance causes a joint destabilization which necessitates a greater recruitment of secondary muscles (Chapters 4, 5 and 6). A greater engagement of secondary muscles promotes strength adaptations that aid in joint stability and core muscle strength, not only reducing the risk of injury, but also improving balance and agonist-synergist coactivation which can aid in sport specific performance. The combined use of elastic and weight resistance is, therefore, not only beneficial in rehabilitation but also in performance strength training, where an increased time under tension throughout the ROM would induce strength adaptations at all muscle lengths, and an increased engagement of secondary muscles would increase 1RM performance by promoting adaptations in all of the muscle groups involved (Bellar *et al.*, 2011; Anderson *et al*. 2008).

9.2.3 Strength training and injury prevention

The architectural adaptations of muscle fibres to resistance training are equally as important as strength gains and should also be considered when devising resistance training programmes. In this thesis, the analysis of muscular activation patterns throughout the ROM revealed that, due to the location of peak muscle activation, elastic training is more likely to induce a shortening of the muscle fibres, while weight training is more likely to induce a lengthening thereof (Brughelli *et al.*, 2010; Alegre *et al.*, 2006; Rassier *et al.*, 1999). Considering that long muscle fibres are stronger when exerted at stretched positions, while short muscle fibres possess less sarcomeres, they are weaker and therefore more prone to injury (Timmins *et al.*, 2016), professionals must consider promoting muscular exertion at stretched positions in order to avoid further injuries. This is especially true for previously injured muscles, as they tend to exhibit shortened fibres after healing (Timmins *et al.,* 2015). Therefore, the use of weights is more advisable than elastic resistance for strength training as it is more likely to induce a lengthening of the muscle fibres, but the combination of the two methods can further enhance performance by increasing time under tension, promoting muscular activation throughout the entire ROM and increasing the recruitment of synergist muscles.

A limitation of the findings contained in this thesis regard the percentage of elastic and weight resistance used in the combined condition. Chapter 6 showed that, despite increasing time under tension throughout the concentric phase, a combination of 50% T + 50% W was not sufficient to produce amplitudes similar to the peak activations elicited by either of the resistances when used alone. Despite this difference, it was speculated that a greater time under tension would still promote greater increases in isokinetic peak torque following a strength training programme, although this was not the case (Chapter 8). It was therefore proposed that a greater percentage of each load should be implemented to exert appropriate levels of activation. A combination of 70% T + 70% W was proposed based on the differences observed in the analytical data (Chapter 6), although further studies are necessary to establish the most appropriate ratio for effective strength and power training.

9.2.4 Eccentric loading

Strength training programmes often include a specific focus on eccentric action as it permits the implementation of greater loads, promoting greater strength and hypertrophic adaptations than concentric training alone (Roig *et al.*, 2008). In addition, eccentric training appears to be beneficial in inducing a lengthening of the muscle fibres, reducing the risk of injury (Franchi *et al.*, 2017; Timmins *et al.*, 2016). The muscular activation patterns portrayed in Chapters 4, 5 and 6 of this thesis established that weight resistance elicits a significantly greater agonist activation than elastic resistance in the eccentric phase, especially at higher movement velocities. This difference is consistent with previous findings (Jakobsen *et al.*, 2014; Aboodarda *et al.*, 2013, 2011; Matheson *et al.*, 2001) and is partially explained by the decreasing applied load that the tubes exerted as they recoiled throughout the extension phase. Therefore, open chain exercises, such as the ones implemented in these studies, would be best performed with weights in order to induce eccentric loading.

In contrast to this statement, however, a study on jump squats documented a greater eccentric activation of the vastus lateralis during the landing phase of the jump following the addition elastic resistance (Cronin *et al.*, 2003). Cronin *et al.*’s (2003) study applied load through a supine squat machine, which reduces the impact forces applied to the joints. Standing jump squats performed with a barbell could potentially produce the same effect, although the weights may place excessive load on the joints upon landing, posing a risk for back and knee injuries (Cleather *et al.*, 2013). Cronin *et al.*’s (2003) findings indicate that elastic resistance could be effectively added to more dynamic exercises such as standing jump squats, possibly through attachments on a waist belt, in order to increase eccentric activation during the landing phase without posing high risks to the participant’s joints. If the elastic tubes are anchored near the feet, the reduction in elastic tension that occurs as the participant descends into the squat would relieve tension on the joints, thus offering a safer application of resistance for eccentric loading.

Eccentric loading is therefore more effectively promoted through the use of weight resistance during open chain exercises, while the addition of elastic resistance can offer a safer application of eccentric load during dynamic exercises.

9.2.5 Power training

A further progression to strength training includes high speed, ballistic or power training, which normally involve weight resisted exercises executed at high velocities. Elastic resistance would not be beneficial for this training modality due to its recruitment of peak activation at the end of the ROM. Power training requires peak activation to occur at the beginning of the ROM in order to promote neuromuscular enhancements such as a reduction in time to peak activation and an increase in rate of force development (Knight and Kamen, 2001; van Cutsem *et al.*, 1998), which cannot be triggered by a progressive load such as the one offered by elastic resistance. The main limitation of power training with weights, however, is the lack of muscular overload at the end of the ROM (Behm *et al.*, 1991). The high initial activation observed in high speed movements with weights generates a momentum that aids in the completion of the movement, without necessitating muscle action at final phases of ROM (Chapter 5) (Behm *et al.*, 1991). By combining unshortened elastic tubes with weights, the increase in elastic tension at the end of the movement may provide the required additional exertion (Chapter 6), ensuring muscular overload throughout the entire ROM, thus maximising strength and power gains. Therefore, power training requires a resistance method that places a high load at initial phases of movement, such as weights, in order to promote adaptations in rate of force development; however, the addition of an elastic resistance can maximise strength gains by ensuring muscular exertion throughout the entire ROM.

9.2.6 Sport-specific training

Finally, although using elastic tubes alone may not provide a high resistance at the beginning of the ROM, they can help develop high movement velocities and may be useful for sports that involve high speed-low resistance movements such as boxing, tae-kwon-do, tennis and athletics. Elastic resistance may in fact be particularly useful in martial arts, where most fighting techniques (punches, kicks) involve high speed-low resistance initial movements followed by high speed-high resistance at impact. The progressive increase in load applied by the tubes mimics this pattern, providing sport-specific training for impact sports. It is also worth mentioning that the versatility of the elastic tubes provides a load that is not dependent on gravity, making them ideal for sport-specific movements such as punching, swinging rackets and sprinting, where the direction of the applied load is not perpendicular to the ground.

Table 9.1 - Summary of the proposed methods of training mentioned in Section 9.2. Recommended loads for weight training are based on the ACSM Position Stand for resistance training (ACSM, 2009), while recommendations for elastic resistance are based on load equivalents specified by Page et al. (2000) and are determined based on conclusions made in this thesis.

	TRAINING STAGE	**RECOMMENDED METHOD**	**RECOMMENDED LOAD**	**RATIONALE**
Rehabilitation	Recent Injury	Tubes	20-40% 1RM unshortened	The progressive load helps avoid abrupt changes in muscle activation and exerts muscles at short lengths, promoting a safer mode of exercise.
	Neuromuscular Rehab	Tubes	40-60% 1RM	The low initial resistance of tubes permits the development of high accelerations without causing abrupt changes in load.
	Strength Rehab	Tubes	40-60% 1RM multiple & shortened	Adding multiple tubes in parallel and shortening their initial length will promote greater muscular activation at initial stages of ROM, aiding the progression towards exerting muscles at long lengths.
		Combined	30-40% 1RM T + 30-40% 1RM W	Combining weights and tubes will place additional load at the beginning of the ROM and will increase time under tension, promoting strength gains across all muscle lengths.
	Repeated Injury Prevention	Tubes	60% 1RM multiple &/or shortened	Tubes will engage synergist and auxiliary muscles, promoting joint stability.
		Weights	60% 1RM	Weights will exert the agonist muscle at long lengths, promoting an increase in the length of its fibres and sarcomere numbers.
Performance	Stability/Core/Proprioception	Tubes	30-80% 1RM shortened	The variability of elastic resistance promotes a greater recruitment of core, postural and auxiliary muscles, promoting joint stability and proprioception.
	Strength	Combined	30-80% 1RM T + 30-80% 1RM W	Combining the two methods ensures muscular exertion throughout most of the ROM and increases synergist activation, enhancing 1RM gains.
	Eccentric Loading	Weights	30-130% 1RM	Weights will ensure muscular overload throughout the lengthening phase of open chain exercises.
		Tubes	NA	Tubes can offer a safer application of load during more complex and dynamic exercises such as jump squats.
	Power	Weights	0-60% 1RM	Weights, contrarily to tubes, will ensure that loads are placed at early phases of movement in high movement velocities
		Combined	0-60% 1RM T + 0-60% 1RM W	Adding unshortened tubes to weights will ensure muscular overload at final phases of movement, maximising strength adaptations throughout the ROM.
	Velocity	Tubes	10-60% 1RM	The progressive load permits the development of higher accelerations.

9.3 Conclusion

In conclusion, elastic and weight resistance elicit peak muscular activation at different phases of the ROM; these patterns become more prominent at increased movement velocities, they complement each other when the two methods are combined and, finally, they are reflected in angle-specific strength adaptations following a training intervention. This supports the theoretical understanding that eliciting muscular activation at different phases of movement is reflected in angle specific strength adaptations and indirectly suggests a change in muscle fibre architecture. These adaptations have important implications for both performance and injury risk, where a shift in peak strength towards shorter muscle lengths may increase the risk of injury and should be carefully considered when designing both rehabilitation and strength programmes. Due to its application of load at the beginning of the ROM, weight training would be more effective in increasing rate of force development during power training, while the addition of elastic resistance would maximise strength gains by activating the muscles throughout a larger portion of the range of motion. A combination of the two methods may be effectively incorporated into periodised strength or power training to overcome a plateau in strength adaptations of trained athletes. In addition, the increased recruitment of auxiliary muscles with elastic resistance make it more effective than weights for improving joint stability and a valuable addition for maximising strength performance by improving agonist-synergist co-activation. Elastic and weight resistance training are therefore equally effective in producing strength adaptations but differ in their application of load throughout the range of motion and therefore in the specificity of their adaptations in the muscle fibres.

9.4 Future research

Despite the depth of investigation offered in the previous chapters, this thesis merely touched upon the basics of muscular activation patterns that occur with elastic resistance and its applications on bicep curl training. However, the findings reported in these studies provide avenues for further research which may be addressed through further research.

One of the main findings of this project regarded the opposing muscular activation patterns observed between elastic and weight resistance, when the directions of applied load are parallel and only one joint is involved in the movement. Further studies could elaborate on patterns of muscular activation in compound exercises (i.e. squats, bench presses, deadlifts etc). Understanding the behaviour of core muscles during elastic resistance training would help determine the appropriate resistance method for holistic training approaches.

Behm (1998) inferred that a combination of both elastic and weight resistance would produce greater strength gains, especially during high speed training. The intervention study, however, suggested that using 50% elastic and 50% weight load was not sufficient to increase gains in isokinetic strength in respect to either method when used alone, despite the clear increase of time-under-tension observed in Chapter 6. Primarily, further studies could establish which percentage of each load would be appropriate in improving training results, followed by an application of the findings in a training intervention. Considering the complexity of strength adaptations, including the number of muscles involved, the position at which muscles are exerted and the ability to co-activate agonist and synergist muscles, intervention studies that compare the use of elastic and weight resistance should test for a number of strength variables, including not only 1 repetition maximum, but also isokinetic and isometric strength of the muscles involved in the movement and combine the use of EMG to determine adaptations in different muscle groups. Using a wide range of strength tests would help assess not only an improvement in the exercise-specific task, but also the overall performance and adaptations of the skeletal system with either method.

Findings reported in this thesis seem to suggest that architectural adaptations may differ between elastic and weight resistance methods, although this was only investigated indirectly through a short intervention study. In order to establish whether or not the implementation of elastic resistance training effectively changes the architecture of the skeletal muscles involved, an invasive observation of muscle cells could help elucidate such a relationship.

Chapter 7 determined that the rate of fatigue of agonist muscles was equal between the elastic and weight conditions in the first 30 repetitions. However, considering that elastic resistance prompts a greater engagement of secondary movers, the point of exhaustion might be reached earlier under elastic resistance as opposed to weight resistance. Further studies may consider investigating metabolic consumption and time to exhaustion when performing identical tasks with elastic or weight resistance. Coupled with an electromyographic analysis of muscular activation throughout the trial, this would help determine how elastic resistance affects the level of engagement of the body as a whole, and how this differs to weight training. Differences in metabolic rates would help determine the best method for weight loss or endurance performance, while differences in muscular engagement and point of exhaustion would help determine the applicability of either method in a variety of strength training disciplines.

Chapter 8 reported lower strength gains when using a combination of elastic resistance and weights in a bicep curl training programme, contradicting Anderson *et al.* (2008) and Bellar *et al.* (2011) who reported greater improvements in 1RM with the same method, in respect to weights. It was speculated that the difference in findings could lie in the different choice of exercise, (one joint vs two joints involved) hence a lower proportion of auxiliary muscles involved, which would have affected the total force output. Considering that Chapters 4, 5 and 6 found a greater engagement of auxiliary muscles in the elastic and combined conditions compared to weights, the improvements reported in the two publications could be due to improved strength in synergist muscles. An electromyographic investigation on all muscles involved in a compound exercise, followed by a training intervention could help evaluate the contribution of secondary muscle adaptations to improvements in performance.

Finally, further research may consider investigating the applicability of elastic training in sport-specific contexts, focusing on the transfer of adaptations from elastic resistance training to sport performance. Having observed the clearly opposing muscular activation patterns elicited by weight and elastic resistance in this study, further studies may also consider investigating the effects of combining the two resistances during power training to understand whether this effectively provides added benefits in lifting performance and in muscular strength throughout the ROM.

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APPENDIX A

Informed consent and PAR-Q

WRITTEN CONSENT TO PARTICIPATE IN THE RESEARCH STUDY:

Comparison of muscular strength adaptations through short term moderate intensity training with weights and elastic tubing.

Statement by participant

- I confirm that I have read and understood the information sheet/letter of invitation for this study. I have been informed of the purpose, risks, and benefits of taking part.
- I understand what my involvement will entail and any questions have been answered to my satisfaction.
- I understand that my participation is entirely voluntary, and that I can withdraw at any time without prejudice.
- I understand that all information obtained will be confidential.
- I agree that research data gathered for the study may be published provided that I cannot be identified as a subject.
- Contact information has been provided should I (a) wish to seek further information from the investigator at any time for purposes of clarification (b) wish to make a complaint.

Contact: ______________________

Participant's Name_____________________________________ Date _____________

Participant's Signature____

Statement by investigator

- I have explained this project and the implications of participation in it to this participant without bias and I believe that the consent is informed and that he/she understands the implications of participation.

Name of investigator ____________________________________ Date _______________

Signature of investigator____

Physical Activity Readiness
Questionnaire - PAR-Q
(revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

→

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ____ DATE ______________________________

SIGNATURE OF PARENT ____ WITNESS ______________________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

CSEP | SCPE

APPENDIX B

Training Diary

EXERCISE LOG DIARY

Participant Name ______________________________ # __________

- Please remember to log all your training sessions in this diary. It is very important that you are truthful in your recordings as this will help with precise analysis of the data provided.
- Please draw a cross over each box once you have completed your session.
- Although not desirable, if you miss a session try to make up for it the following day (and state so in the table). Any comments can be made to the side if necessary.

Cross out each set of repetitions once completed

	Day	**date**	**Sets x Reps**	**1**	**2**	**3**	**Comments**
	Lab session		*3 x 10*	*10*	*10*	*10*	**Maximum rest time between sets: 30 seconds.**
Week 1	Monday		3 x 10	10	10	10	
	Wednesday		3 x 10	10	10	10	
	Friday		3 x 10	10	10	10	
Week 2	Monday		3 x 10	10	10	10	
	Wednesday		3 x 10	10	10	10	
	Friday		3 x 10	10	10	10	
Week 3	Monday		3 x 15	15	15	15	
	Wednesday		3 x 15	15	15	15	
	Friday		3 x 15	15	15	15	
Week 4	Monday		3 x 15	15	15	15	
	Wednesday		3 x 15	15	15	15	
	Friday		3 x 15	15	15	15	
Week 5	Monday		3 x 20	20	20	20	
	Wednesday		3 x 20	20	20	20	
	Friday		3 x 20	20	20	20	
Week 6	Monday		3 x 20	20	20	20	
	Wednesday		3 x 20	20	20	20	
	Friday		3 x 20	20	20	20	
Week 7	Monday		3 x 25	25	25	25	
	Wednesday		3 x 25	25	25	25	
	Friday		3 x 25	25	25	25	
Week 8	Monday		3 x 25	25	25	25	
	Wednesday		3 x 25	25	25	25	
	Friday		3 x 25	25	25	25	

Keep in a safe place. To be returned to the researchers upon completion.

APPENDIX C

SPSS output for statistical tests on the concentric phase of the biceps brachii during the bicep curl

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
T0_1	.167	16	.200*	.920	16	.169
T0_2	.131	16	.200*	.957	16	.608
T0_3	.182	16	.165	.939	16	.338
T0_4	.132	16	.200*	.961	16	.678
T0_5	.118	16	.200*	.967	16	.780
T0_6	.152	16	.200*	.953	16	.536
T0_7	.134	16	.200*	.957	16	.611
T10_1	.179	16	.179	.910	16	.118
T10_2	.148	16	.200*	.927	16	.220
T10_3	.143	16	.200*	.943	16	.390
T10_4	.160	16	.200*	.930	16	.245
T10_5	.122	16	.200*	.949	16	.473
T10_6	.105	16	.200*	.938	16	.329
T10_7	.211	16	.056	.953	16	.543
T20_1	.219	16	.039	.922	16	.183
T20_2	.139	16	.200*	.948	16	.458
T20_3	.173	16	.200*	.935	16	.291
T20_4	.155	16	.200*	.956	16	.584
T20_5	.219	16	.039	.918	16	.159
T20_6	.180	16	.174	.922	16	.179
T20_7	.142	16	.200*	.959	16	.651
W_1	.115	16	.200*	.989	16	.998
W_2	.219	16	.039	.857	16	.017
W_3	.185	16	.146	.908	16	.107
W_4	.152	16	.200*	.942	16	.379
W_5	.160	16	.200*	.947	16	.439
W_6	.147	16	.200*	.903	16	.090
W_7	.160	16	.200*	.962	16	.707

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

PEAK EMG

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
method	.436	10.555	5	.062	.650	.754	.333

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: method

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
method	Sphericity Assumed	676.533	3	225.511	3.037	.039	.178	9.110	.672
	Greenhouse-Geisser	676.533	1.950	346.893	3.037	.066	.178	5.922	.534
	Huynh-Feldt	676.533	2.262	299.114	3.037	.056	.178	6.868	.579
	Lower-bound	676.533	1.000	676.533	3.037	.103	.178	3.037	.368
Error(method)	Sphericity Assumed	3118.967	42	74.261					
	Greenhouse-Geisser	3118.967	27.304	114.232					
	Huynh-Feldt	3118.967	31.665	98.499					
	Lower-bound	3118.967	14.000	222.783					

a. Computed using alpha = .05

Pairwise Comparisons

Measure: MEASURE_1

(I) method	(J) method	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-5.333	2.684	.067	-11.091	.424
	3	-9.467*	3.464	.016	-16.896	-2.037
	4	-5.200	4.393	.256	-14.622	4.222
2	1	5.333	2.684	.067	-.424	11.091
	3	-4.133	2.503	.121	-9.502	1.235
	4	.133	2.746	.962	-5.757	6.023
3	1	9.467*	3.464	.016	2.037	16.896
	2	4.133	2.503	.121	-1.235	9.502
	4	4.267	2.665	.132	-1.448	9.982
4	1	5.200	4.393	.256	-4.222	14.622
	2	-.133	2.746	.962	-6.023	5.757
	3	-4.267	2.665	.132	-9.982	1.448

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

INTERGRATED EMG

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
method	.372	12.591	5	.028	.702	.829	.333

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept
Within Subjects Design: method

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
method	Sphericity Assumed	2589976.067	3	863325.356	18.825	.000	.573	56.476	1.000
	Greenhouse-Geisser	2589976.067	2.106	1229594.458	18.825	.000	.573	39.653	1.000
	Huynh-Feldt	2589976.067	2.488	1040841.893	18.825	.000	.573	46.844	1.000
	Lower-bound	2589976.067	1.000	2589976.067	18.825	.001	.573	18.825	.981
Error(method)	Sphericity Assumed	1926116.933	42	45859.927					
	Greenhouse-Geisser	1926116.933	29.489	65316.177					
	Huynh-Feldt	1926116.933	34.837	55289.623					
	Lower-bound	1926116.933	14.000	137579.781					

a. Computed using alpha = .05

Pairwise Comparisons

Measure: MEASURE_1

(I) method	(J) method	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-233.867*	62.326	.002	-367.543	-100.190
	3	-527.000*	79.280	.000	-697.038	-356.962
	4	-464.067*	102.677	.000	-684.286	-243.847
2	1	233.867*	62.326	.002	100.190	367.543
	3	-293.133*	40.862	.000	-380.775	-205.492
	4	-230.200*	83.307	.015	-408.877	-51.523
3	1	527.000*	79.280	.000	356.962	697.038
	2	293.133*	40.862	.000	205.492	380.775
	4	62.933	85.824	.475	-121.140	247.007
4	1	464.067*	102.677	.000	243.847	684.286
	2	230.200*	83.307	.015	51.523	408.877
	3	-62.933	85.824	.475	-247.007	121.140

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

MUSCULAR ACTIVATION PATTERNS – CONCENTRIC PHASE

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
condition	.643	6.061	5	.301	.829	1.000	.333
rom	.000	101.424	20	.000	.349	.406	.167
condition * rom	.000	.	170	.	.222	.312	.056

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept

Within Subjects Design: condition + rom + condition * rom

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
condition	Sphericity Assumed	7223.793	3	2407.931	19.124	.000	.560	57.372	1.000
	Greenhouse-Geisser	7223.793	2.488	2903.821	19.124	.000	.560	47.575	1.000
	Huynh-Feldt	7223.793	3.000	2407.931	19.124	.000	.560	57.372	1.000
	Lower-bound	7223.793	1.000	7223.793	19.124	.001	.560	19.124	.983
rom	Sphericity Assumed	17441.325	6	2906.887	11.814	.000	.441	70.881	1.000
	Greenhouse-Geisser	17441.325	2.092	8336.195	11.814	.000	.441	24.717	.992
	Huynh-Feldt	17441.325	2.439	7152.418	11.814	.000	.441	28.808	.997
	Lower-bound	17441.325	1.000	17441.325	11.814	.004	.441	11.814	.894
condition * rom	Sphericity Assumed	5546.620	18	308.146	8.265	.000	.355	148.774	1.000
	Greenhouse-Geisser	5546.620	3.991	1389.671	8.265	.000	.355	32.989	.997
	Huynh-Feldt	5546.620	5.619	987.066	8.265	.000	.355	46.445	1.000
	Lower-bound	5546.620	1.000	5546.620	8.265	.012	.355	8.265	.766

a. Computed using alpha = .05

Pairwise Comparisons

Measure: MEASURE_1

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-5.279[*]	1.220	.001	-7.880	-2.678
	3	-10.819[*]	1.760	.000	-14.571	-7.068
	4	-8.184[*]	1.623	.000	-11.644	-4.724
2	1	5.279[*]	1.220	.001	2.678	7.880
	3	-5.541[*]	1.313	.001	-8.339	-2.742
	4	-2.905[*]	1.200	.029	-5.463	-.348
3	1	10.819[*]	1.760	.000	7.068	14.571
	2	5.541[*]	1.313	.001	2.742	8.339
	4	2.635	1.762	.155	-1.120	6.390
4	1	8.184[*]	1.623	.000	4.724	11.644
	2	2.905[*]	1.200	.029	.348	5.463
	3	-2.635	1.762	.155	-6.390	1.120

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

MUSCULAR ACTIVATION PATTERNS – CONCENTRIC PHASE POST-HOC TEST FOR THE FIRST 20° OF ROM

Within-Subjects Factors

Measure: MEASURE_1

CONDITION	Dependent Variable
1	T0_1
2	T10_1
3	T20_1
4	W_1

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
CONDITION	.319	15.687	5	.008	.622	.707	.333

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. Design: Intercept

Within Subjects Design: CONDITION

b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
CONDITION	Sphericity Assumed	2438.553	3	812.851	41.390	.000
	Greenhouse-Geisser	2438.553	1.866	1306.871	41.390	.000
	Huynh-Feldt	2438.553	2.121	1149.807	41.390	.000
	Lower-bound	2438.553	1.000	2438.553	41.390	.000
Error(CONDITION)	Sphericity Assumed	883.740	45	19.639		
	Greenhouse-Geisser	883.740	27.989	31.574		
	Huynh-Feldt	883.740	31.813	27.780		
	Lower-bound	883.740	15.000	58.916		

Pairwise Comparisons

Measure: MEASURE_1

(I) CONDITION	(J) CONDITION	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-3.859*	.899	.004	-6.588	-1.130
	3	-6.477*	1.175	.000	-10.047	-2.908
	4	-16.670*	1.535	.000	-21.331	-12.009
2	1	3.859*	.899	.004	1.130	6.588
	3	-2.619	1.380	.463	-6.808	1.571
	4	-12.811*	1.882	.000	-18.524	-7.099
3	1	6.477*	1.175	.000	2.908	10.047
	2	2.619	1.380	.463	-1.571	6.808
	4	-10.193*	2.177	.002	-16.803	-3.583
4	1	16.670*	1.535	.000	12.009	21.331
	2	12.811*	1.882	.000	7.099	18.524
	3	10.193*	2.177	.002	3.583	16.803

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

APPENDIX D

Additional illustrations of muscular activation patterns from Chapter 5

9.5 Bicep Curl

Biceps Brachii

Muscular activation increased significantly (p<.001) with movement velocity under both elastic (Figure 0.1) and weight (Figure 0.2) resistance. The elastic condition presented more prevalent differences (p<.001) between velocities throughout most of the concentric phase (Figure 0.1); while the weight condition (Figure 0.2) only showed a significant effect (p<.001) at early stages of the ROM (160° to 80° elbow angle) of both the concentric and eccentric phase.

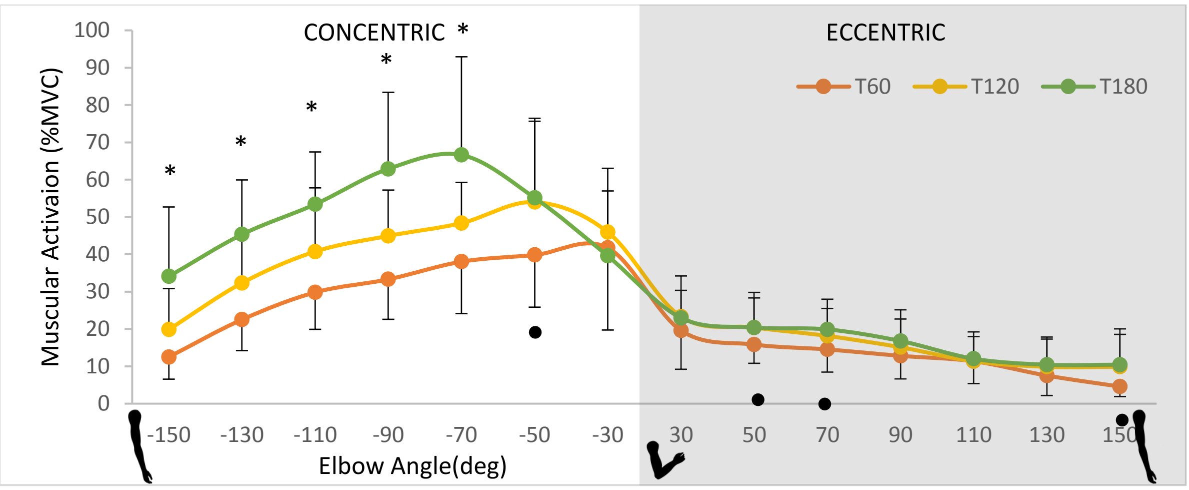

*Figure 0.1 – Mean muscular activation (n=22) of the biceps brachii muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. *Significant difference (p<.001) between all conditions; ● Significant difference (p<.001) between T60 and all other velocities.*

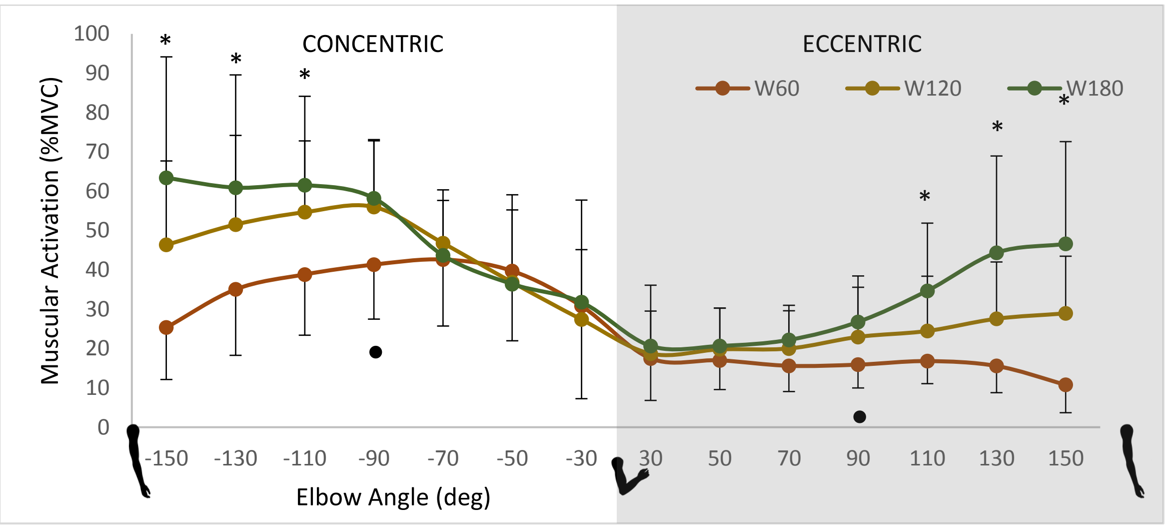

*Figure 0.2 - Mean muscular activation (n=22) of the biceps brachii muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl, at three different velocities (60 deg·s-1, 120 deg·s-1, 180 deg·s-1) using free weights as a resistance method. Significant difference between all velocities for both the concentric and eccentric phase (p<.05). *Significant difference between all conditions; ● significant difference between T60 and all other conditions.*

Triceps Brachii

In the elastic condition, overall triceps activation increased significantly with movement velocity in both eccentric and concentric phases ($p<.001$; $p=.038$) and, similarly to the biceps brachii, peaks in muscular activation occurred 20° earlier in the ROM with higher movement velocities. Weight resistance elicited similar trends in peak activation, which also occurred earlier in the ROM with increased movement velocity, but differences in activation patterns with weight resistance did not reach statistical significance (Figure 0.4).

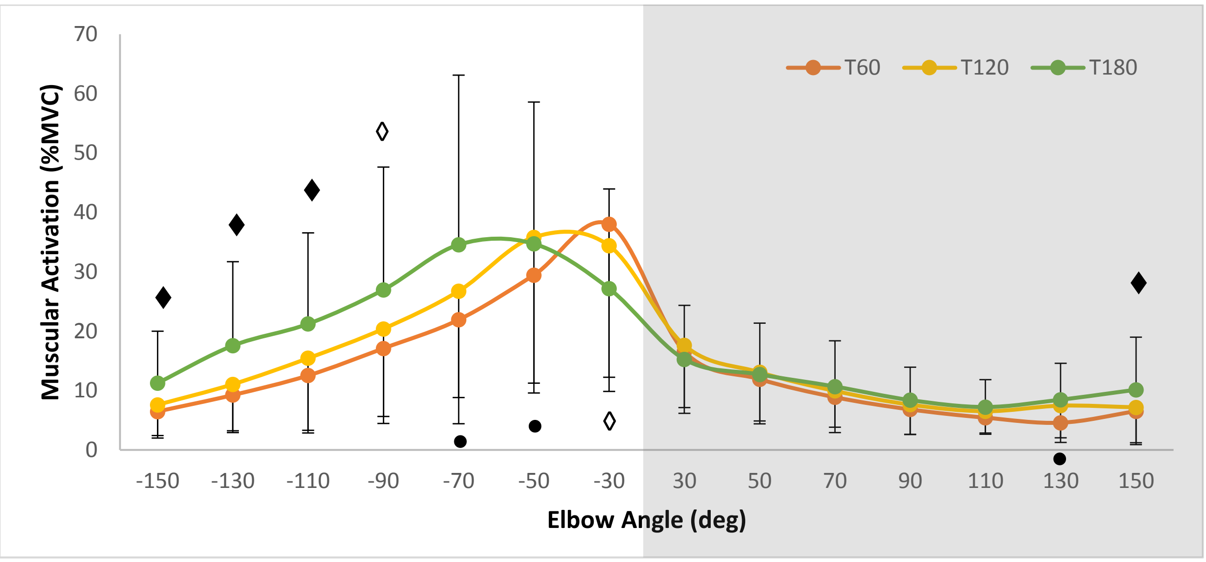

Figure 0.3 – Mean muscular activation (n=22) of the triceps muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. Significant difference between all velocities in the concentric (p<.05) and only T60 being different (p<.05) from all other velocities in the eccentric phase. ◊ T60 significantly different (p<.05) from T180; ♦T180 significantly different (p<.05) from all other velocities; ● T60 significantly different (p<.05) from all other velocities.

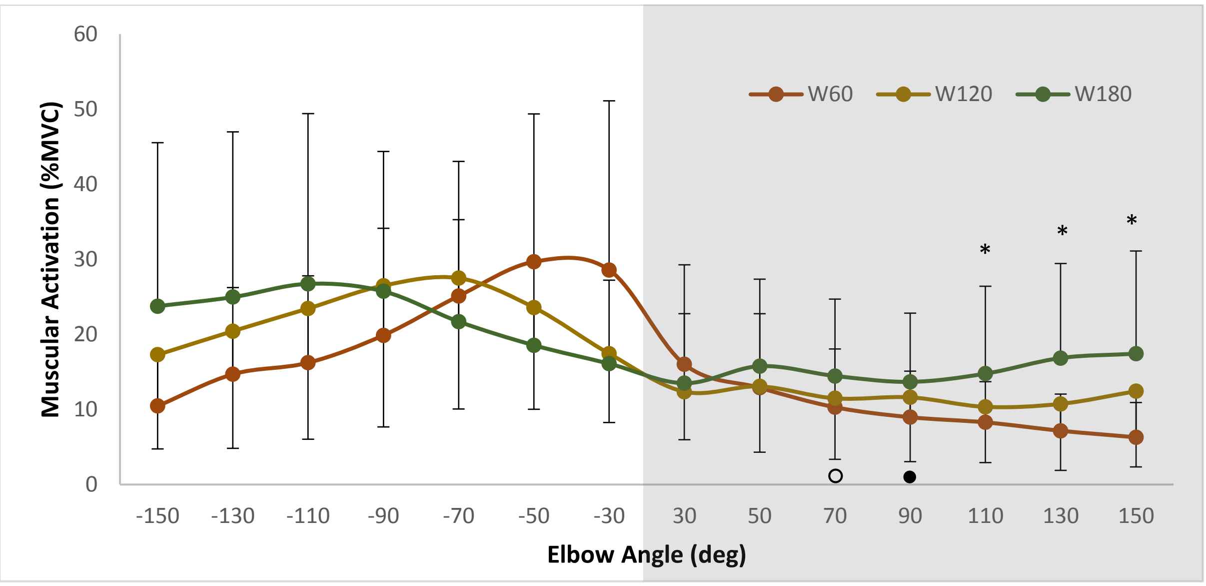

*Figure 0.4 - Mean muscular activation (n=22) of the triceps muscle per every 20° of ROM, throughout the entire range of motion of a bicep curl, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using weights as a resistance method. * Significant difference (p<.05) between all velocities;. ● W60 significantly different (p<.05) from all other velocities; ○ W60 significantly different (p<.05) from W180.*

9.6 Leg Extension

Rectus femoris

When performing the leg extension, overall activation of the rectus femoris significantly increased (p<.001) with movement velocity in the concentric phase under both elastic (Figure 0.5) and weight (Figure 0.6) resistance. Eccentric activation of the Rectus femoris also increased significantly (p<.001) with velocity in the weight condition (Figure 0.6), but was not affected under elastic resistance (Figure 0.5).

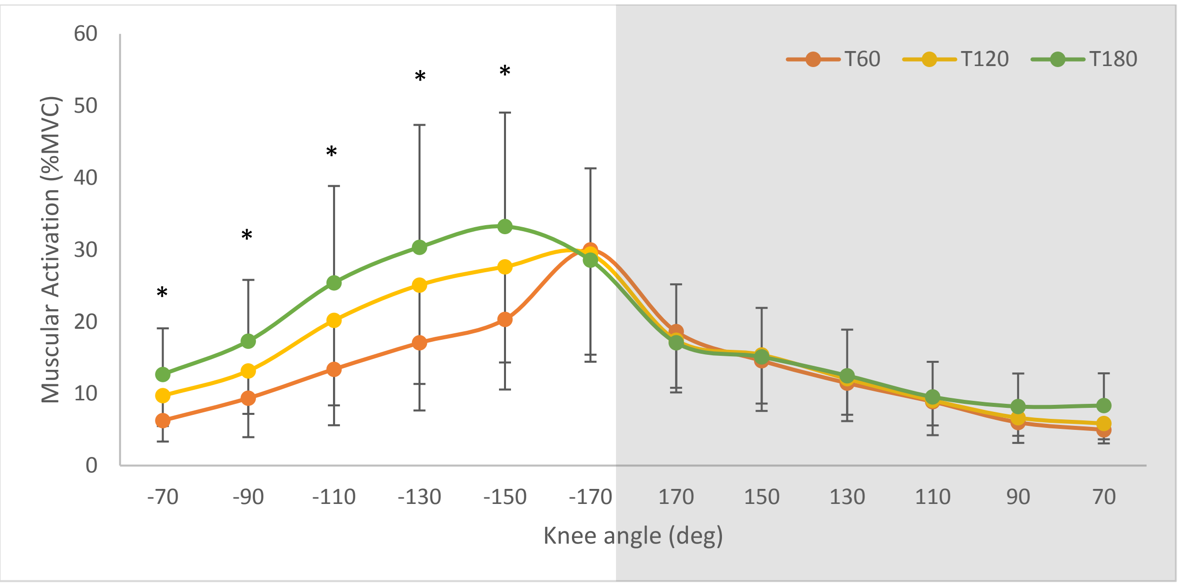

*Figure 0.5 – Mean muscular activation (n=22) of the Rectus Femoris per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. * Significant difference (p<.05) between all conditions.*

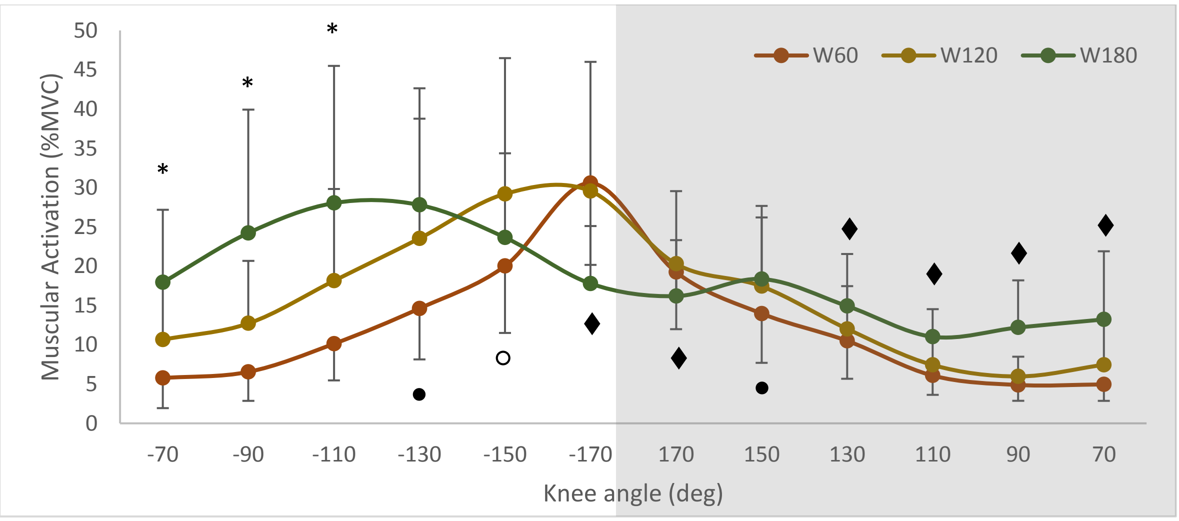

*Figure 0.6 – Mean muscular activation (n=22) of the Rectus Femoris per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using free weights as a resistance method. *Significant difference (p<.05) between all conditions; ● W60 is significantly different (p<.05) from all other conditions; ○W60 and W120 are significantly different (p<.05); ♦ T180 is significantly different (p<.05) than all other conditions.*

Vastus Medialis

Muscular activation of the vastus medialis significantly increased (p≤.001) with movement velocity throughout the concentric phase with both elastic (Figure 0.7) and weight resistance (Figure 0.8). Activation also increased at the end of the eccentric phase under both resistance methods, but only reaching statistical significance (p=.044) for the elastic condition.

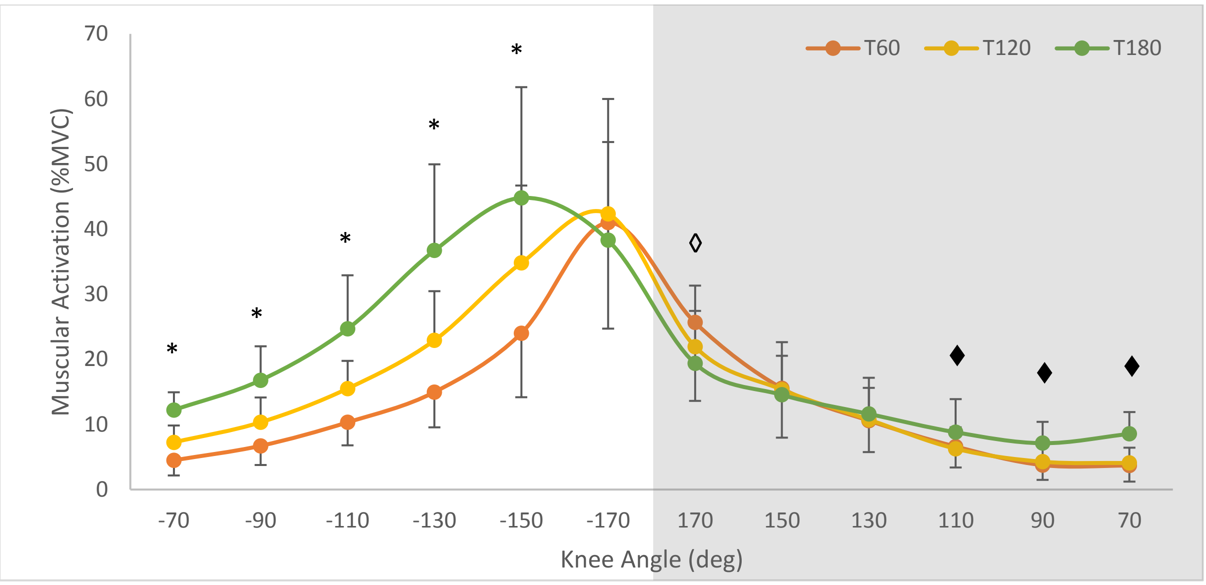

*Figure 0.7 – Mean muscular activation (n=22) of the Vastus Medialis per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. *Significant difference (p<.05) between all conditions; ♦ T180 is significantly different (p<.05) from all other conditions; ◊ T60 significantly different (p<.05) from T180.*

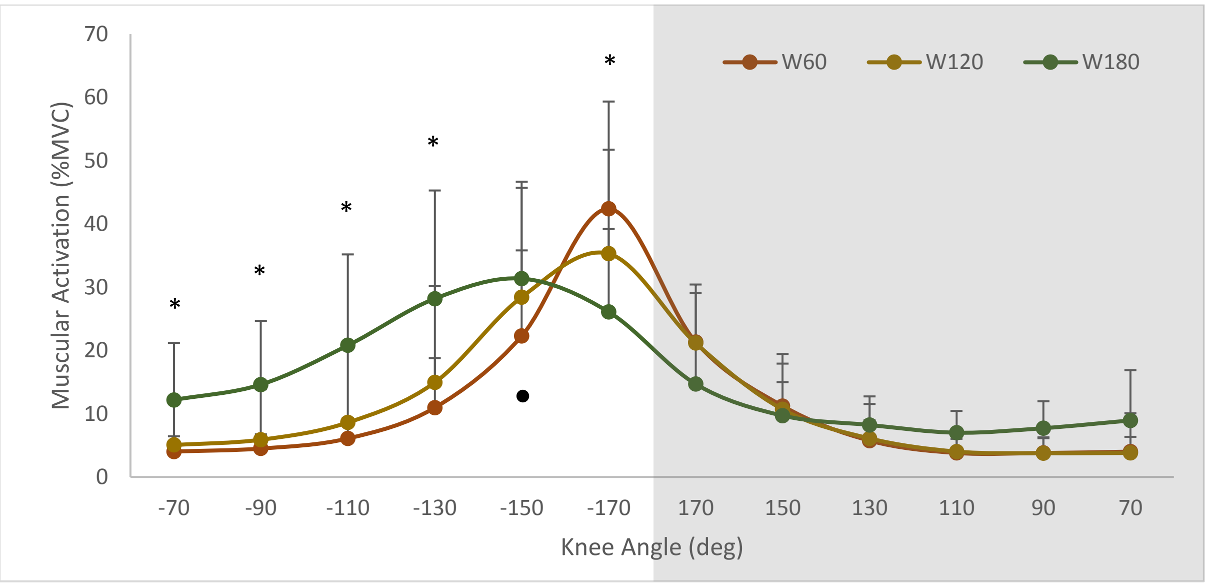

*Figure 0.8 – Mean muscular activation (n=22) of the Vastus Medialis per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using weights as a resistance method. *Significant difference (p<.05) between all conditions; ● T60 is significantly different (p<.05) from all other conditions.*

Vastus Lateralis

Similarly to the vastus medialis, muscular activation of the vastus lateralis increased significantly (p<.001) with movement velocity in the concentric phase of both the elastic (Figure 0.9) and weight resistance (Figure 0.10).

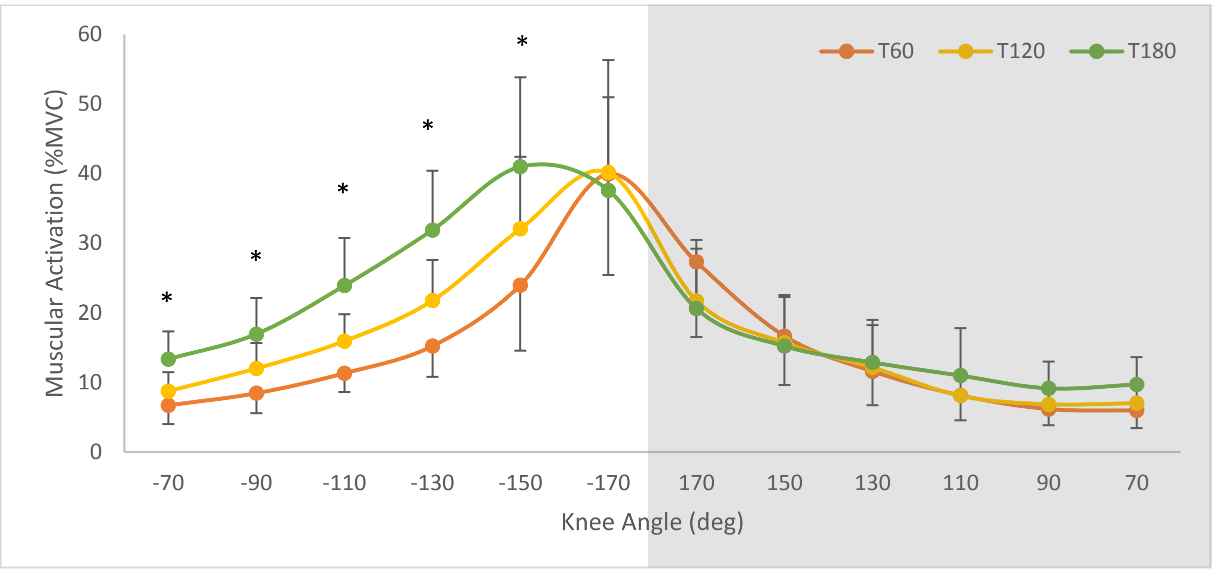

*Figure 0.9 - Mean muscular activation (n=22) of the Vastus Lateralis per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. *Significant difference (p<.05) between all conditions.*

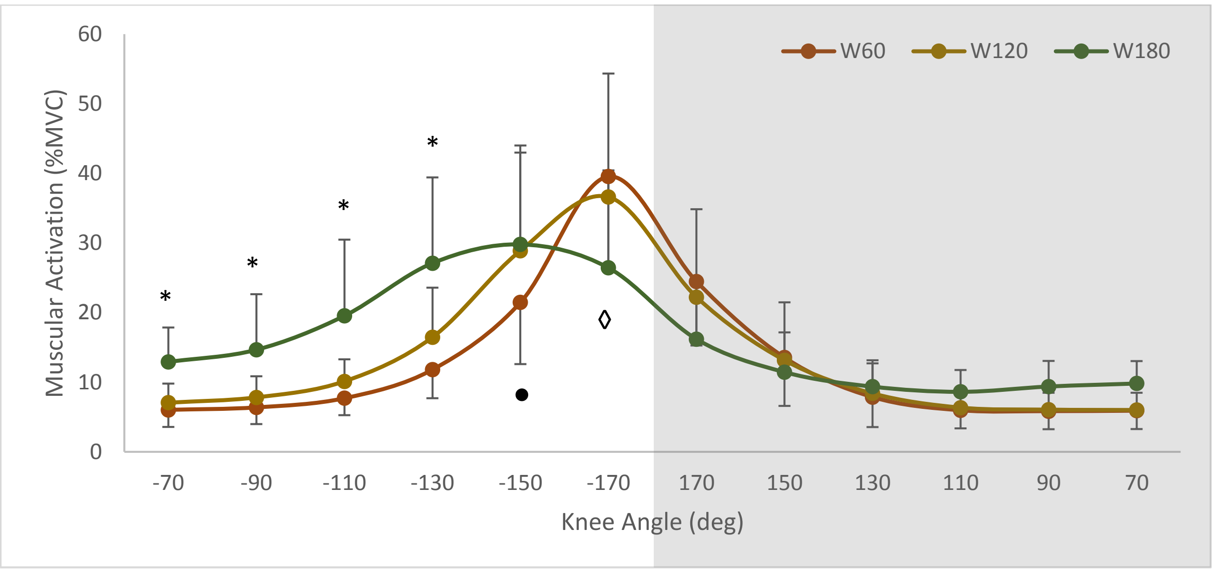

*Figure 0.10 - Mean muscular activation (n=22) of the Vastus Lateralis per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. *Significant difference (p<.05) between all conditions; ◊ T180 is significantly different (p<.05) from all other conditions.*

Biceps Femoris

Muscular activation of the biceps femoris was significantly higher at 60°s^{-1} at the end of the concentric phase under both elastic (p=.024) (Figure 0.11) and weight resistance (p=.001) (Figure 0.12).

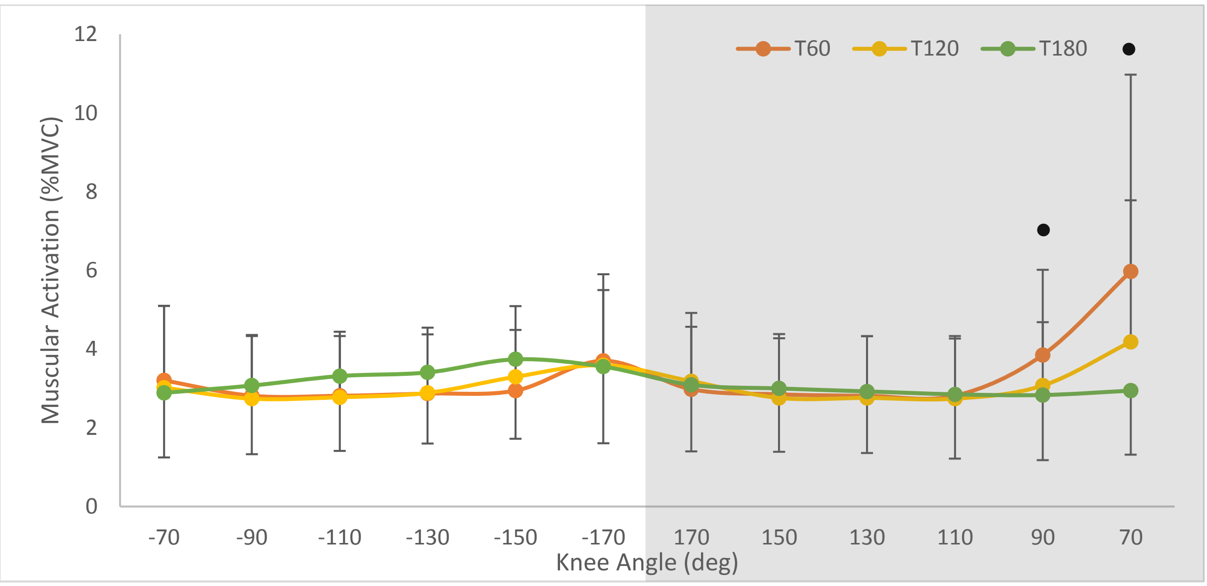

Figure 0.11 - Mean muscular activation (n=22) of the Biceps Femoris per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. ●*T60 is significantly different (p<.05) than all other conditions.*

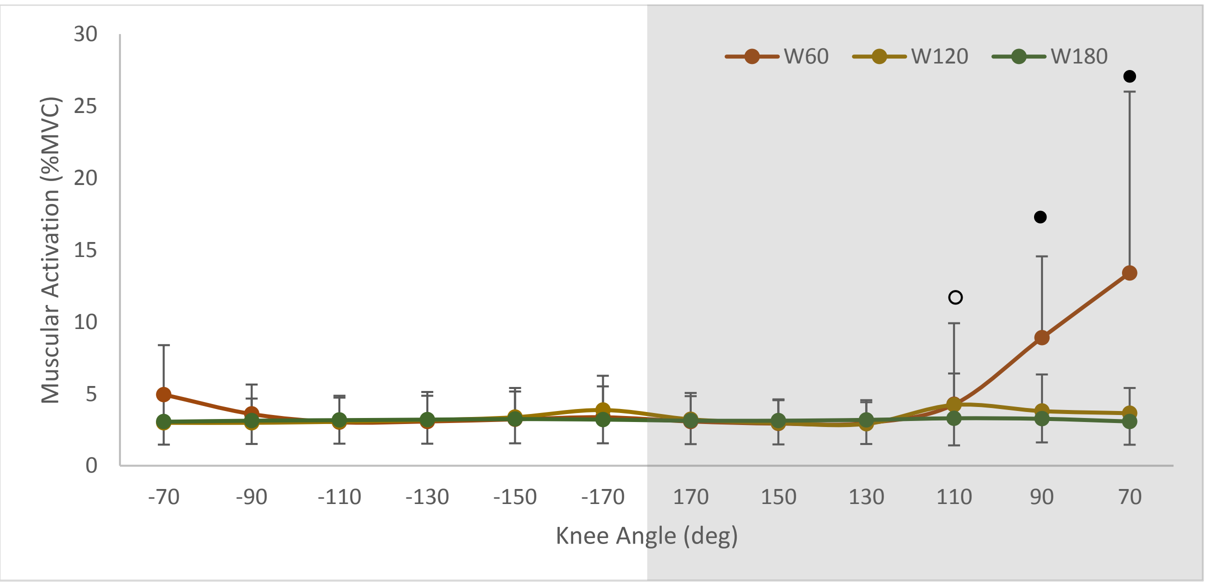

Figure 0.12 - Mean muscular activation (n=22) of the Biceps Femoris per every 20° of ROM, throughout the entire range of motion of a leg extension, at three different velocities (60°s^{-1}, 120°s^{-1}, 180°s^{-1}) using elastic tubes as a resistance method. ●*T60 is significantly different (p<.05) than all other conditions;* ○ *T60 is significantly different (p<.05) than T180.*