Neuro-Mechanical Analysis of Eccentric Overload of Elbow Flexors

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Abstract

Eccentric overload in training settings utilizes loads higher than concentric one repetition maximum (1RM). There is no clear definition of eccentric "failure" or 1RM using conventional weights, so eccentric 1RM is estimated to be between 145-190% concentric 1RM. Historically, the highest intensity used for eccentric overload is typically 120% of concentric 1RM despite little research using conventional weights with higher eccentric intensities. The purpose of this study was to conduct an exploratory neuro-mechanical analysis of different intensities of elbow flexors eccentric overload using free weights by examining angular kinematics during contraction. Twenty male participants with weight training experience had unilateral concentration curl isometric peak torque assessed on a Humac Norm Dynamometer and concentric 1RM assessed with dumbbells while biceps brachii electromyography (EMG) and elbow joint angle were recorded. Angles were recorded using a custom made electrogoniometer and elbow joint torque was estimated using inverse dynamics. Participants were randomly assigned in counter balanced order to perform eccentric actions at 120%, 140%, 150%, 160% and 170% concentric 1RM with 4 minutes rest between. Variables included peak torque, angular velocity at peak torque, impulse, power, mean EMG, and EMG normalized to peak. Data were analyzed using repeated measures ANOVA or a Friedman test. Angular velocity at peak torque was significantly lower for 120% (65.3 ± 40.8°/s) compared to all other conditions (range: 65.3 ± 40.8 to 162.1 ± 75.2°/s; $p<0.01$). Peak torque for all conditions (range: 98.2 ± 16.2 to 108.2 ± 21.6 Nm) was significantly higher than isometric peak torque (77.4 ± 16.8Nm; $p<0.05$). Peak torque at 160% (108.2 ± 21.6Nm) was significantly higher than at 120% (98.2 ± 16.2Nm; $p<0.05$). Power for 140-170% (range: 166.2 ± 85.7W to 265.8 ± 111.3W) was significantly higher than power at 120% (79.9 ± 66.8W; $p<0.05$). Impulse was highest at 120% (56.1 ±

54.6Nms) compared to all other conditions (range: 56.2 ± 54.6 to 9.6 ± 3.8Nms; $p \leq 0.05$). Impulse at 140% (20.6 ± 11.8Nms) was significantly higher than 170% (9.6 ± 3.8Nms; $p<0.05$). Isometric mean EMG (0.792 ± 0.285 mV) was significantly higher than all eccentric conditions (range: 0.654 ± 0.313 to 0.533 ± 0.259mV; $p<0.05$) with no difference between eccentric conditions for mean EMG or EMG normalized to peak. It was concluded that compared to 120%, eccentric overload with intensity ranging from 140-170% concentric 1RM involves minimal increases in peak torque and no change in EMG activation. Intensities above 120% enhance power and decrease impulse. This research has implications on future training prescription of eccentric exercise.

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Dedication

I would like to dedicate this thesis first to my parents for having always created the optimal conditions for me to develop myself personally and academically. Thank you for always having the drive to put me through the best schools you could afford, for all the extra-curricular activities (too many to list) and, most importantly, for having the patience to put up with a teenager “rock-star-wannabe”. Thank you for raising me the way you did.

Secondly, I would like to dedicate this thesis to my grandmothers (*in memoriam*) for all the unforgettable conversations and for always helping me develop a true sense of pride, integrity and relentlessness when facing difficulties.

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Chapter 1

Scientific Framework

1.1 Introduction

Eccentric muscle actions cause muscles to be forcibly lengthened while being contracted (Proske and Morgan, 2001) and are characterized by generating high muscle forces, unique control strategies by the central nervous system (Enoka, 1996), more severe and prolonged myofibrillar disruption, soreness, and force deficit (Bamman et al., 2001), decrease in active tension, shift in optimum length for active tension and rise in passive tension (Proske and Morgan, 2001). Besides damage to muscle fibers, it is also believed that following eccentric training, there is interruption of optimal performance of muscle sense organs and proprioception as well as an increase in number of in-series sarcomeres in muscle fibers (Rassier et al., 1999, Proske and Morgan, 2001). Contrary to what happens in concentric muscle actions, the maximal torque generated by muscles during eccentric contractions is less affected by changes in velocity, meaning the force-velocity relationship observed in concentric contractions is not observed in eccentric contractions (Enoka, 1996).

Eccentric training has shown to induce greater gains in strength and hypertrophy than concentric (Farthing and Chilibeck, 2003; Hillard-Robertson et al., 2003; Paddon-Jones et al., 2005; Roig et al., 2008) and these gains in strength tend to be specific to the mode of training utilized, meaning that eccentric training induces higher gains in eccentric strength than in isometric and concentric strengths (Hortobagyi et al., 1996; Seger et al., 1998).

The effects of training with eccentric muscle actions that utilize intensity higher than that of concentric one repetition maximum (1RM) have been studied since the 1970s (Johnson et al., 1976; Jones 1973). In 1987, Jones and Rutherford stated that eccentric knee flexion 1RM was, on average, 145% higher than the concentric 1RM. In 2010, Friedman-Bette et al. demonstrated that it could be as high as 190% of concentric 1RM under different requirements for execution of eccentric knee flexion exercise.

To my knowledge, no study has attempted to define the most productive intensity of eccentric overload in terms of increase in strength and/or hypertrophy, in part because there is no clear definition of eccentric 1RM and there is no clear method to estimate one's eccentric 1RM in a conventional weight training setting. Further to this, there is little information as to the appropriate intensity of concentric 1RM for a given muscle group or the type of exercise utilized – multi-joint or single joint. Therefore, the primary objective of this work is to conduct an exploratory neuro-mechanical analysis of different intensities of eccentric overload on elbow flexors and attempt to establish usable criteria to define failure during eccentric exercises for elbow flexors utilizing conventional weights.

1.2 Review of Literature

1.2.1 Myofibrillar Disruption and Eccentric Contractions

In order to investigate eccentric 1RM, the participants of this study performed eccentric muscle actions with elbow flexors; such muscle actions are highly associated with onset of pain and soreness (Asmussen, 1952) and they cause more muscle injuries through mechanical trauma than isometric and concentric muscle actions (Talag, 1973). As this may affect force-generating capacity during eccentric actions, the mechanisms for muscle damage during eccentric actions is reviewed here. During a high intensity eccentric action, the actin-myosin cross-bridges are likely mechanically disrupted, rather than undergoing an ATP-dependent detachment (Enoka, 1996). Besides this phenomenon, damage to skeletal muscle fibrils, membrane and ion transport mechanisms are noticeable (Dolezal et al., 2000). Moreover, abnormalities such as "sarcolemmal disruption, dilation of the transverse tubule system, distortion of myofibrillar components, fragmentation of the sarcoplasmic reticulum, lesions of the plasma membrane, cytoskeletal damage, changes in the extracellular myofiber matrix, and swollen mitochondria" (Enoka, 1996) are evident post-eccentric exercise. Moreover, the delayed onset of muscle soreness that follows eccentric training seems to be more related to an inflammatory response than to remodeling of musculo-tendinous tissues or muscular structural damage and that gains in strength resulting from eccentric training are more related to changes in neuromuscular activation than to muscular hypertrophy (Enoka, 1996).

Evidence of muscular damage following eccentric muscular actions include decreased performance, morphological changes in the muscles affected, delayed onset of muscle soreness and elevation of myocellular enzymes (such as creatine kinase) in the blood stream (Dolezal et al., 2000).

1.2.2 Passive Stiffness of the Elbow Joint

In this study, participants were instructed to generate maximal resistance while their elbow joints were extended due to the torque generated by weights heavier than what participants could lift concentrically. Besides the volitional torque generated by the elbow flexors, the overall resistance to the extension of the elbow joint includes the passive stiffness of the elbow joint, which is the non-volitional resistance to full extension of the elbow joint generated by structures that compose the elbow joint (Howell et al., 1993). Passive stiffness of resting muscles is determined by connective tissue only at longer sarcomere lengths (>2.6-3.0μm), low level cross-bridge interactions, presence of titin in the sarcomeres (Caiozzo, 2000) and increased volume of muscle compartment (Howell et al., 1993). Besides these muscular factors, non-muscular factors such as joint capsules and skin contribute to the passive stiffness of the elbow joint (Howell et al., 1993). Titin is a large molecule – with over 20,000 amino acids – which extends from Z-line to M-line. It is hypothesized that its segment lying within the I-band has elastic properties, acting like a molecular spring (Caiozzo, 2000). A number of titin isoforms have been identified and the predominant isoforms, as well as changes in overall quantities of titin and percentages of isoforms within a muscle, are believed to be responsible for different passive properties of such muscle (Caiozzo, 2000). Unloading muscles has the potential to induce a decrease in material property coefficient under passive conditions turning the muscle into a more mechanically compliant tissue by reduction of absolute volume of titin within sarcomeres or transition of faster isoforms to slower isoforms (Caiozzo, 2000).

Eccentric exercises induce stretching of muscles while under tension and induce a release of calcium into the myoplasm, which may be exaggerated in injured muscles, contributing to an apparent increased stiffness more noticeable at full extension or flexion (Howell et al., 1993). Passive elastic stiffness at full extension or flexion of unloaded elbow flexors may reach the magnitude of 2.0-2.5Nm even though throughout the mid-range it stays at around 1.4 $Nm.rad^{-1}$ (Hayes and Hatze, 1977). Passive elastic torque function is linear on the medial third of elbow range of motion but non-linear when considering the entire elbow range of motion (Hayes and Hatze, 1977).

1.2.3 Length-Tension Relationship

The determination of eccentric 1RM of elbow flexors – one of the purposes of this study – is dependent upon many factors. Maximal volitional eccentric torque generated by the elbow flexors during this study varied depending on their length, velocity of contraction and level of stimulation while performing the motion (Brugheli and Cronin, 2007). This maximal torque is heavily dependent on the muscle’s length because force generation is, on a cellular basis, the result of the overlapping of myosin and actin in active sarcomeres (Caiozzo, 2000). This relationship between length of the muscle and the force it is capable of generating is named length-tension relationship and is affected by active components at shorter muscle lengths, and by passive components at longer muscle lengths; specifically tendon compliance and by muscle architecture (Brughelli and Cronin, 2007). The literature suggests that the optimal length-tension relationship is achieved when sarcomere length lies between 2.0 and 2.5µm and decreases linearly with the increase in sarcomere length (Caiozzo, 2000). Therefore, the maximal torque generated by a muscle (or muscle group) changes with changes in muscle length, which is a consequence of changes in angle joint. Singh and Karpovich (1966) state that peak isometric and eccentric torques of arm flexors are achieved with 100^{o} of elbow flexion and that peak concentric torque is achieved with 120^{o} of elbow flexion.

There is controversy surrounding the possibility of altering the length-tension relationship. The literature suggests that immobilization of a joint in a lengthened position induces an increase in sarcomeres in-series (sarcomereogenesis), resulting in longer muscle fibers and immobilization in a shortened position induces reduction of sarcomeres in-series, resulting in shorter muscle fibers (Caiozzo, 2000). Brughelli and Cronin (2007) suggest that the greatest shifts in the length-tension relationship have occurred in the quadriceps and biceps brachii. The authors also state that despite the fact that eccentric exercise interventions have the potential to cause a shift in the length-tension relationship, pennation angle (of pennate muscles) and fiber type composition changes as a result of eccentric exercise intervention have little impact on the shift. Brughelli and Cronin (2007) suggest that two possible shifts can occur: an acute shift due to muscular inflammation after the exercise intervention and a chronic shift due to sarcomereogenesis and increase in passive tension at longer muscle lengths – a result of disruption of the muscle's passive components. The mechanisms behind this shift in the length-tension relationship are hypothesized to be a transformation of active contractive elements into passive elements, damage to myotendinous attachments and to calcium handling structures (Brughelli and Cronin, 2007). It has also been suggested that overstretched sarcomeres increases tissue compliance, shifting the muscle's length-tension curve towards higher tensions at higher muscle lengths, which is commonly noticeable post eccentric exercise interventions (Proske and Morgan, 2001).

1.2.4 Force-Velocity Relationship

The angular velocities at which eccentric muscle actions happened during this study were a consequence of the weight elbow flexor muscles were under. This force-velocity relationship is inverse and hyperbolic in nature (Caiozzo, 2000). Under concentric conditions, slow velocity contractions are induced by higher resistive forces and faster velocity contractions are induced by lower resistive forces. Under eccentric conditions, higher weights result in faster velocities and lower weights result in lower velocities.

Under eccentric conditions, contractions have a three-dimensional nature and are regulated by force, velocity and time and the force-velocity relationship cannot be described in a planar curve (such as under concentric conditions) due to the influence of time, which is the third axis (Caiozzo, 2000). Besides, muscle fiber type is known to affect the force-velocity relationship under concentric conditions, but it remains unclear the extent to which it affects this relationship under eccentric conditions (Caiozzo, 2000). Moreover, according to Caiozzo (2000), under eccentric conditions, even though it is known that within the first 1-2% stretch of a muscle there is a drop in force generation it is not clear whether such drop is a result of the rapid detachment of cross-bridges or the rupture of "weaker" sarcomeres.

Strength level has an impact on the pattern of the torque-velocity relationship as assessed under isokinetic conditions (Hortobagyi and Katch, 1990). Individuals of higher absolute strength levels will show a curve that differs from that of individuals of lower absolute strength level. Low strength individuals produce a curve with a plateau at low velocities under concentric conditions and no increase in force under higher velocities under eccentric conditions. High strength individuals show change in torque under lower concentric velocities and increased torque under increased eccentric velocities (Hortobagyi et al., 1990). However, these findings are based purely on results using isokinetic contractions and less is known about the shift in the torque-velocity relationship when using free weights, particularly with eccentric overload contractions where the amount of external weight directly relates to the velocity of contraction.

Shifts in the force-velocity curve are possible and could be a consequence of increased stiffness of the muscle – which is a product of the cross-sectional area, a direct result of addition of sarcomeres in parallel (Caiozzo, 2000). Eccentric training has the potential to not only increase absolute torque at each velocity, but to alter the shape of the force-velocity curve in able-bodied individuals (Gabriel et al., 2006). Much less is known about the force-velocity curve using free weights, and how it is altered after eccentric training. Practically it is much more difficult to assess high velocity eccentric actions using free weights in a conventional setting, therefore many free weight training studies have used loads of around 105-120% of concentric 1RM (Hakkinen and Komi, 1983; Bamman et al., 2001; Brandenburg and Docherty, 2002; Doan et al., 2002; Kraemer et al., 2006; Ojasto and Hakkinen, 2009, Guilhem et al., 2010a), which emphasizes a slow velocity eccentric contraction. Since there is no clear definition of eccentric 1RM in conventional weight-training settings, it is challenging to determine appropriate or optimal training loads for eccentric training using free weights. Eccentric 1RM is hard to identify because there is no clear definition of "failure" during an eccentric repetition using free weights.

1.2.5 Failure and Eccentric

Failure during concentric exercises can be defined as the inability to execute a full repetition of the exercise throughout a predetermined range of motion or when the weight cannot be lifted without compensatory movement (Munn et al., 2005) but determining failure during an eccentric contraction seems to be much more complex. Researchers commonly determine a minimum time frame as the cutoff for a "valid repetition" to be performed; this way, if a repetition is performed faster than predetermined minimum it is deemed "failure" (Jones and Rutherford, 1987).

1.2.6 Isokinetic Exercises

For eccentric exercises such as bench press or those involving axial loading such as squats it is inherently dangerous to attempt to define an eccentric 1RM using conventional weights due to the possibility of injury. Much of what we know about the ratio of peak concentric and eccentric torque relationships comes from using isokinetic dynamometers, where maximal eccentric efforts can be executed quite safely; however, the results obtained from assessments and training performed with dynamometers may not be applicable to the conventional weight training setting, which employ weight machines and free weights.

Besides training with free weights and weight machines, eccentric training can be performed with isokinetic dynamometers. The earliest models were developed in 1964 as a manually operated model and redesigned in 1966 so that the external force needed for testing the participant was supplied by an electrical motor, instead of the investigator (Singh and Karpovich, 1967). Isokinetic dynamometers are technologically advanced equipment utilized by researchers to assess skeletal muscle function (Drury et al., 2006; Miller et al., 2007; Remaud et al., 2007; Holm et al., 2008; Marchant et al., 2009; McHugh et al., 2010) as well as to perform training studies under controlled circumstances (Paddon-Jones et al., 2005; Nickols-Richardson et al., 2007; Sakamoto et al., 2009; Krentz and Farthing, 2010; Remaud et al., 2010). However, due to the cost of these machines, they are not commonly found in rehabilitation and training settings.

1.2.7 Isotonic or Isoinertial Exercises

Training with weight machines and free weights is commonly named "isotonic training" even though a more accurate term for this type of training would be "isoinertial mechanical solicitation", since the external load on the muscles being trained changes as the lever arm varies in length with the changing angle within the predetermined range of motion (Guilhem et al., 2010b). Another appropriate term is "isoload external resistance", which refers to the fact that the external load does not change throughout the exercise (Guilhem et al., 2010b), but the angular momentum does. The literature suggests that with isotonic exercises, motions have variable angular velocity and stimulate greater response from the neuromuscular system at the weakest mechanical point of the range of motion while the neuromuscular system works submaximally at other angles (Kowaleski et al., 1995).

Isotonic weight training has been shown to induce greater gains in strength than isokinetic, when gains in strength were relative to the number of sessions performed by participants (Guilhem et al., 2010a). When comparing studies that report gains in strength evoked by isotonic and isokinetic training, Guilhem et al. (2010a) reported that isotonic training increases strength by 1.1 ± 1.0% per training session for a mean duration of 7.5 ± 3.4 weeks and the authors suggested the reason for this greater gain in strength could be the greater neuromuscular activation after isotonic training. They also reported the average increase in strength following eccentric isokinetic training – also relative to the number of sessions performed by participants – was 0.6 ± 3.0% per training session with mean duration of 10.6 ± 4.9 weeks.

Moreover, higher agonist muscle activity is required during isotonic exercises, which induces higher co-activation of antagonist muscle groups, leading to increased joint stability, thus, aiding in injury prevention (Aagard et al., 1995; Miller and Croce, 2000; Remaud et al., 2007). The literature suggests that for isokinetic motions, the resistance to the movement is equal to the force (or torque) exerted by the participant; this way, the participant benefits from the fact that torque is maximal at all points of the range of motion (Guilhem et al., 2010a; Guilhem et al., 2010b). Since isokinetic training is not feasible without expensive equipment, it would be beneficial to investigate peak torque (and corresponding angular velocities) acquired with conventional "isotonic" exercises that utilize free-weights so that future training studies could determine the feasibility and applicability of overload eccentric training at different percentages of concentric 1RM.

1.2.8 Eccentric Training and Prescription

Researchers and therapists recognize the advantages of emphasizing or overloading the eccentric phase of contraction in training and rehabilitation environments, but there is little consensus on the most effective way to incorporate it. Eccentric actions within training and rehabilitation settings have been investigated in two major ways: with overload eccentric training and with dynamic accentuated external resistance. Overload eccentric training is a type of weight training that utilizes only eccentric actions with a weight higher than the concentric one repetition maximum (1RM) (Schroeder et al., 2004; Kraemer et al., 2006; Norrbrand et al., 2008; Friedmann-Bette et al., 2010). Overload eccentric training between 105-125% concentric 1RM has been investigated in several studies (Hakkinen and Komi, 1983; Bamman et all, 2001; Brandenburg and Docherty, 2002; Doan et al., 2002; Kraemer et al., 2006; Ojasto and Hakkinen, 2009; Guilhem et al., 2010a) and many of these did not provide any justification for the choice of percentage of concentric 1RM (Hakkinen and Komi, 1983; Bamman et al., 2001; Brandenburg and Docherty, 2002; Doan et al., 2002; Guilhem et al., 2010b).

Dynamic accentuated external resistance training is a dual-phase training approach (concentric and eccentric) with a different intensity of concentric 1RM for each phase (Godard et al., 1998; Brandenburg and Docherty, 2002; Doan et al., 2002; Ojasto and Hakkinen, 2009; Friedmann-Bette et al., 2010). During dynamic accentuated external resistance training the participant performs the concentric motion with constant weight and during the eccentric phase extra load is added by a “spotter” or by an external mechanism; this extra weight is removed once another repetition of concentric phase is about to begin. Doan et al. (2002) demonstrated that when overload eccentric bench press utilizing 105% concentric 1RM immediately precedes a new 1RM assessment participants were able to acutely increase their 1RM by about 3%. The better understanding of the implications of eccentric overload on the neuromuscular systems may lead to better prescriptions of dynamic accentuated external resistance training. However, in order to accurately prescribe eccentric training loads in conventional settings such as those described above, more research is necessary to understand the kinematics of eccentric overload contractions using free weights. With these eccentric contractions, there is an inherent trade-off between time under tension and external load whereby the velocity of contraction is driven by the external load under influence of gravity. For the development of effective eccentric training protocols it is important to thoroughly investigate this trade-off during various intensities of eccentric overload contractions.

1.2.9 Historical Context

The investigation of eccentric overload based on concentric 1RM can be dated back to the work of Johnson et al. (1976), who investigated strength gains induced by two different training protocols – concentric training with resistance of 80% concentric 1RM and eccentric training with resistance of 120% concentric 1RM. They justified the choice of 120% 1RM by stating that "such load is near the maximum that can be used (…) since loads heavier than this accelerate the stretching muscles too rapidly" (Johnson et al., 1976). Additionally, they mention that according to Jones (1973) the "maximum response to eccentric training" is obtained when the weight is low enough for the subject to be able to "stop the stretching force if he is able." However, Jones (1973) is not a scientific study, but the opinion of an individual who claims that "intensity produces results – force causes injuries" and that "the intensity of the exercise must be as high as possible – but the force must be as low as possible". Jones (1973) also claimed that one of his acquaintances gained 12 pounds of muscle in 2 weeks by performing "negative only workouts" (Jones 1973). While the opinions of Mr. Jones may have some application and indeed lead to effective training results, there is virtually no scientific rigor surrounding his early work or his recommended eccentric overload of 120% concentric 1RM. Jones (1973) was cited not only by Johnson et. al. (1976) but also by Atha (1981) and Fleck and Kramer (2004); these three latter works were cited by other 1522 works throughout the years.

1.2.10 Eccentric 1RM

A controversial aspect of eccentric training is how to determine the eccentric 1RM as a percentage of assessed concentric 1RM. Jones and Rutherford (1987) examined the effects of three weight-training regimes on isometric strength of the knee extensors in eleven males and one female. The authors found that the maximum weight lowered during the eccentric phase of the training was, at times, 145% of the weight lifted during the concentric phase through a knee range of motion from 45^o to 180^o. However, the investigators had predetermined that the eccentric phase of this motion should last between 2 and 3 seconds and if it lasted less than 2 seconds the repetition was considered a failure. The participants performed eccentric knee extensions of 135^o between 2 and 3 seconds with average angular velocity between 67.5^o/s and 45^o/s (Jones and Rutherford, 1987). One potential drawback of using a time constraint as a method of determining eccentric failure is it emphasizes the angular impulse but could decrease the peak torque generated during the contraction and therefore could underestimate eccentric 1RM.

Contradicting these findings, Friedmann-Bette, et al. (2010) assessed thirty male athletes with strength training background and who participated in sports where explosive strength was predominant – Judo, track and field jumps or sprints, and basketball. The participants trained both legs' knee extensors and were instructed to perform maximal voluntary contractions during the concentric phase and to exert maximal resistance during the eccentric phase of every repetition of the training, which was performed either on a conventional training device or on a computer-driven device that allowed eccentric weight to be manipulated. One of the major findings of the study was that the eccentric weight was, at times, 190% of the concentric weight (Friedmann-Bette et al., 2010).

1.3 Statement of the Problem and Hypotheses

1.3.1 Statement of the Problem

To my knowledge, no studies have investigated eccentric 1RM on elbow flexors and there is paucity in the literature when it comes to defining the optimal range of percentage of concentric 1RM for overload eccentric training with conventional equipment. Since the current literature seems to be based on what has been effective previously and on historical opinion there is an apparent need to establish an appropriate recommendation for overload eccentric training based on relative concentric loads. However, before this can be achieved it is important to attempt to determine an effective way to define and measure eccentric overload or 1RM using conventional weights. Moreover, it is necessary to understand how a muscle's torque generation and angular velocity – a product of the overload utilized – will change throughout the range of motion when limbs are subject to different intensities of eccentric overload.

Therefore, this work is an exploratory neuromechanical analysis of generation of peak torque, angular velocity at peak torque, mean EMG, power and impulse when the elbow flexors are subject to different intensities of eccentric overload. Moreover, this work intends to establish usable criteria to define "failure" during an eccentric elbow flexion.

1.3.2 Hypotheses

The primary hypothesis is that peak torque will continue to increase with the increasing intensities of eccentric overload, contradicting the classic idea that loads higher than 120% concentric 1RM will stretch the muscles too rapidly rendering them unable to develop maximum tension, which was suggested by Jones (1973) and Johnson et al. (1976) and validating the findings of Friedmann-Bette et al. (2010) by showing an increase in peak torque at intensities of eccentric overload higher than 120% concentric 1RM.

The secondary hypothesis is that angular velocity at peak torque is expected to increase with increasing intensity of eccentric overload; a direct consequence of the increase of the weight of the dumbbells handled by the participants.

The third hypothesis is that signs of neuromuscular inhibition – such as significant reduction in EMG – will be noticed during the highest intensities of concentric 1RM (170%) since it is much higher than 150% concentric 1RM, which Jones (1987) and Bamman et al. (2001) suggest being the upper limit of eccentric strength in relation to concentric strength.

In addition to addressing the variables mentioned in the hypotheses, we will be investigating angular velocity at peak torque, mean EMG, normalized mean EMG (percentage of isometric EMG acquired during assessment of isometric peak torques on the dynamometer), power, impulse, average angular velocity, angle at peak torque, torque at 90^o and peak torque as a percentage of calculated maximal isometric torque. Calculated maximal isometric torque is the torque necessary to stop the forearm-dumbbell system at 90^o of elbow flexion. These exploratory variables will serve to gain further insight into the neuro-mechanical function of the elbow joint system during eccentric overload of elbow flexors.

Chapter 2

Methods

2.1 Study Design

This study followed a cross-sectional quantitative observational model in which participants performed eccentric exercises of the elbow flexors exercises against different loads as determined by relative intensity of their concentric 1 RM for the same exercise. Participants were assigned loads of 120%, 140%, 150%, 160% and 170% of their elbow flexion concentric 1RM in a randomized order. Such loads were selected in order to conduct an investigation comprising eccentric overload as low as that utilized by Johnson. et al. (1976) through 170% concentric 1RM, which is a conservative approach to the intensity of concentric 1RM described by Friedmann-Bette et al. (2010) since there are differences in characteristics (mainly strength and training history) between the participants of this study and those of the Friedmann-Bette et al. (2010) study.

2.2 Participants

A sample of twenty male participants between 18 and 40 years of age were recruited in Saskatoon. Participants were eligible if they had been performing resistance training – which included elbow flexion exercises – three times per week for a minimum of four weeks. Criteria for exclusion were any fracture to the dominant limb (test limb) within twelve months prior to the participant's involvement in the study as well as any muscular and/or tendon soreness on the test limb that, on the opinion of the participant, could have compromised maximal force generation on the day of each data collection session. Participants were asked to refrain from using any anti-inflammatory medication and from performing upper body weight lifting exercises within 48 hours of data collection sessions. Participants' characteristics are displayed in Table 2.1.

Table 2.1 – Participants' Characteristics

Data listed as Means ± Standard Deviation

Age (years)	25.5 ± 4.9
Height (meters)	1.80 ± 0.06
Weight (Kg)	81.6 ± 10.8
Handedness	14.4 ± 6.2
Concentric 1RM (Kg)	23.1 ± 3.6
1RM: body weight (%)	28.6 ± 4.7

Handedness was determined by the modified 10-item Waterloo Handedness Questionnaire. A score of +20 signifies absolute right hand dominance; a score of -20 signifies absolute left hand dominance.

2.3 Procedures

On the first day participants filled out the consent form (appendix B) weight lifting experience questionnaire (appendix C) and the Waterloo Handedness Questionnaire (appendix D) in order to determine the test limb (dominant limb) and also had their height, weight and the distance from elbow to wrist, distance from elbow to center of gravity of weight, distance from elbow to center of gravity of forearm, distance from elbow to center of gravity of hand recorded (appendix E).

Participants performed a 5-minute warm-up on a cycle ergometer and were instructed to sit on the chair of the Humac NORM Dynamometer (CSMi, Stoughton, MA, USA). A single EMG electrode was placed on the belly of the biceps brachii of the test limb (described in Section 2.5 below). Participants were placed in the correct position for the isometric strength test for elbow flexion of the dominant arm using the "concentration curl" position (sitting down on the chair with both feet on the footrest, torso leaned forward, elbow of the test arm placed on the medial aspect of the distal thigh, holding the handle while maintaining the arm perpendicular to the floor) and all the dynamometer settings were recorded for each participant (appendix F).

Once the participant was in the correct position, the dynamometer was calibrated at 90^{o} of elbow flexion with 0^{o} of shoulder flexion and they had a 9 second learning trial period to perform submaximal isometric elbow flexion against the dynamometer. After this trial, there was a 1 minute rest period and participants were instructed that there were three test sets, each one 3 seconds long, during which they had to exert maximal force against the arm of the dynamometer while the generated torque and EMG signals were recorded. Each set was separated by a 1 minute rest period.

After the 3 test sets the participants had a 4 minute rest period sitting down on a chair while a custom built electrogoniometer was placed on their test limb, held in place by Velcro straps (appendix G). After the rest period, participants sat on a the chair and assumed the concentration curl position (appendix H) with elbow of the dominant arm placed against the medial aspect of the distal ipsilateral thigh, a few inches proximal to the knee, arm (humerus) perpendicular to the ground and hand of the non-dominant arm resting on its ipsilateral thigh.

The 1RM test – performed utilizing the protocol developed by the National Strength and Conditioning Association (Earle, 2006) – consisted of three to five sets, with increased intensity in each set, and 2 to 4-minute rest periods in between sets so the participant could gradually reach the 1RM (appendix I). In order to properly execute the 1RM attempts participants were reminded to maintain their arm perpendicular to the ground and not lean back, which would alter the size of the moment arm of the forearm-dumbbell system, facilitating the lifting of the weight by the participant, which would result in a false higher 1RM.

The adjustable spinlock dumbbell system utilized during this study was composed of two 25lb plates, four 10lb plates, two 5lb plates and two 2.5lb plates. The dumbbell handle with its two locking nuts weighed 5.5lbs and the addition of two extra nuts increased the weight of this system to 6lbs. This system allowed the necessary sensitivity to ensure the relative eccentric loads were accurately applied.

On the second day participants had to warm up on the stationary cycle and had one EMG electrode placed on the belly of the biceps brachii of the test limb and followed the protocol for isometric testing utilized during the first day of assessment. After isometric testing the participants sat down on the chair utilized on the first day and had the electrogoniometer placed on their test limb.

After a 4 minute rest period, the participants started the eccentric assessment, which consisted of 3 repetitions of "free fall" followed by 3 repetitions of "maximal effort", for the 5 weight conditions utilized for this study: 120%, 140%, 150%, 160% and 170% of their assessed concentric 1RM. During the three "free fall" repetitions, the dumbbell was lifted by the investigator to the highest angle of elbow flexion possible, without any help from the participant, who was instructed to "relax the biceps" and maintain the grip on the dumbbell as well as maintain the arm perpendicular to the ground. After reaching the shallowest possible angle of elbow flexion, the investigator moved the dumbbell up and down slowly while saying to the participant to "relax the biceps" and suddenly released the dumbbell. The free fall condition was included to serve as a baseline parameter – a non-resisted fall of the dumbbell-arm system.

After the three "free fall" repetitions, the investigator lifted the dumbbell to the highest elbow flexion while the participant was required to maintain a firm grip onto the dumbbell and the investigator instructed the participant to "pull up" and released the dumbbell after the participant had initiated a strong contraction of the elbow flexors in an attempt to hold the dumbbell. All "free fall" and maximal effort conditions were performed while EMG and elbow joint angle were recorded. A 4-minute rest period was given between sets and the order in which the weights were utilized in each set was randomized so as to reduce the effects of fatigue on each individual set throughout the 5 sets (appendix I).

Throughout the free-fall and eccentric exercises participants assume the concentration curl position (appendix H) and were reminded once again to maintain their arms (humerus) perpendicular to the ground throughout all repetitions. Shoulder movement, forward or backward, during the eccentric repetitions would have changed the size of the moment arm of the forearm-dumbbell system resulting in a discrepancy between the readings of the electrogoniometer and the real position of the forearm in relation to the ground.

A crash plate composed of plywood and foam mats was utilized in order to minimize noise as well as limit the maximal elbow extension to 150^o so as to reduce the chances of injury due to overextension of the elbow joint.

2.4 Electrogoniometry

A custom built electrogoniometer consisting of two aluminum rods connected to a 10k Ohms, 0.5 Watt potentiometer (Mode Electronics, Burnaby, BC) was utilized to record the change in elbow joint angle. One rod was strapped to the participant's arm and the other to the participant's forearm while the potentiometer was placed at the fulcrum of the elbow joint. Each rod was strapped with Velcro straps to two different anchorage points to the participant's upper arm and two anchorage points to the participant's forearm (appendix G). Information from the electrogoniometer was recorded using custom written software (described on section 2.8 below). The change in joint angle over time was used to calculate instantaneous velocity at each joint angle and acceleration of the joint through the range of motion.

The electrogoniometer was fed through a National Instruments connector box (Model BNC 2090, TX, USA) and linked to a computer with Labview 8.6 software (National Instruments, QC, Canada) and a NI A/D card which supplied 5V to the electrogoniometer in order to be calibrated. The voltage going through the electrogoniometer was collected and recorded for 5 seconds while the rods of the electrogoniometer were forming a 20^o angle. The same measurements were also taken at increments of 10^o until a maximum angle of 190^o. The correlation between the angle of the rods of electrogoniometer and the voltage going through the potentiometer at each angle between 20^{o} and 190^{o} was $R^2 = 0.999$ (Figure 2.1) achieved on a single calibration procedure which anticipated the start of data collection.

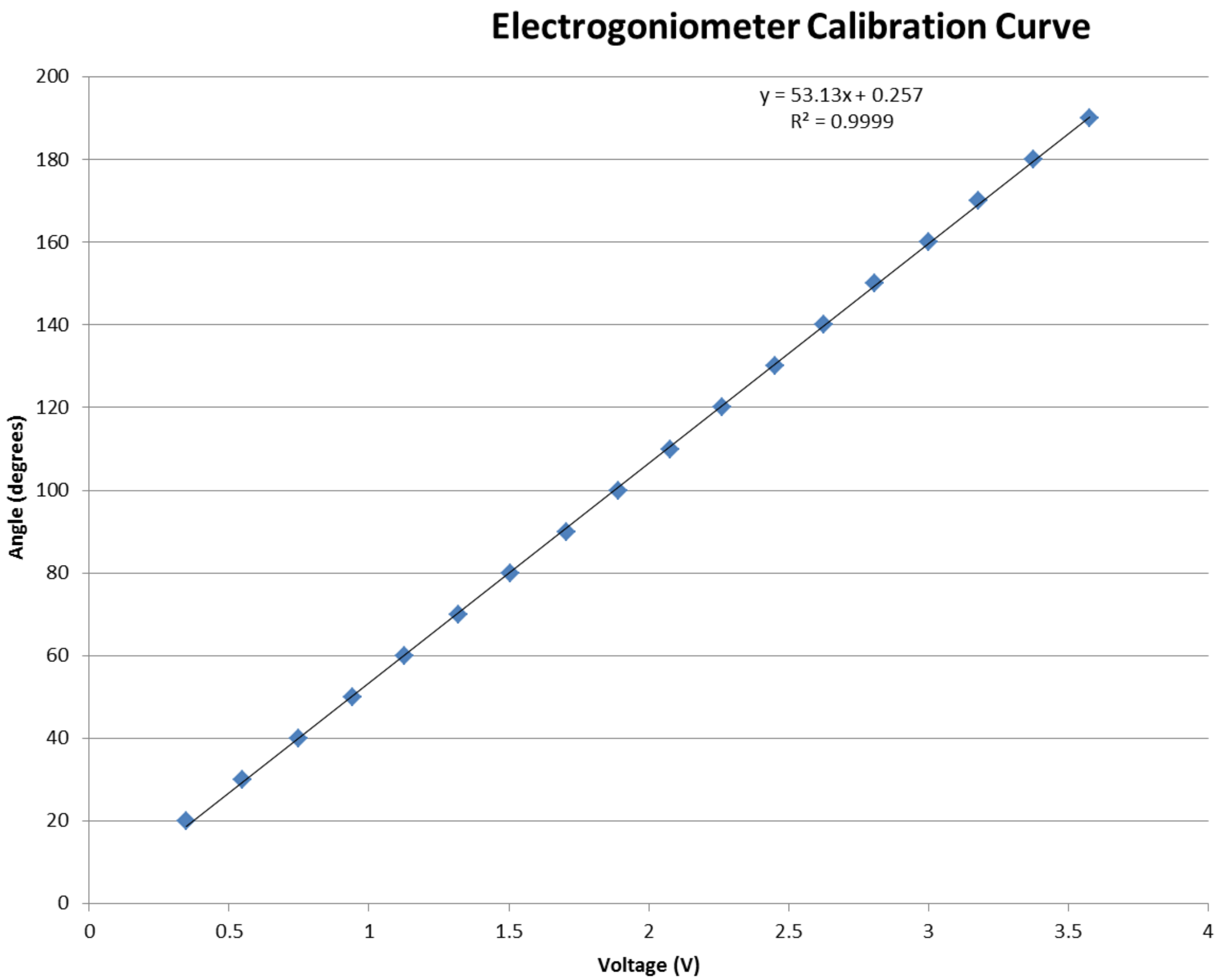

Figure 2.1 – Angle of electrogoniometer × voltage
Calibration curve was acquired on a single calibration procedure prior to start of data collection.

2.5 Electromyography

Electromyography was utilized to record muscle activation throughout each isometric and eccentric elbow flexion. Raw EMG data was collected utilizing a Delsys Bagnoli-4 EMG System (Boston, MA, USA). Participants were sitting down on a chair with their elbows flexed at 90^{o} and the electrode was placed along the line between the fossa cubit and the acromial process, at the first third of such line from the fossa cubit and the reference electrode was placed on the wrist (Hermens 2012). The EMG main amplifier unit included single differential electrodes with a bandwidth of 20 ± 5 Hz to 450 ± 50 Hz, a 12 dB/octave cutoff slope, and a maximum output voltage frequency of ± 5 V. The gain per channel was 1K for the biceps brachii muscle. The system noise is <1.2 μV (rms). The electrodes were two silver bars (10 mm x 1 mm diameter) spaced 10 mm apart with a Common Mode Rejection Ratio (CMRR) of 92 dB.

2.6 Data Acquisition

Custom software written in Labview Version 8.6 was used to acquire signal from the electrogoniometer and EMG data simultaneously. Each channel was acquired at a sampling rate of 1000 Hz. An analog-to-digital (A to D) converter was used to convert the analog signals from each device to digital signals displayed in the Labview interface.

2.7 Variables of Interest

Variables of interest were peak torque, angular velocity at peak torque, mean EMG, normalized mean EMG (expressed as a percentage of isometric EMG acquired during assessment of isometric peak torques on the dynamometer), power, impulse, average angular velocity, angle at peak torque, torque at 90^{o} and peak torque as a percentage of calculated maximal isometric torque (the necessary magnitude of torque at necessary to stop the forearm-dumbbell system at 90^o of elbow flexion which is calculated based on the weight utilized and the measurements of the forearm).

The eccentric torque generated by the participants (the torque generated by the elbow flexors while the participants attempt to control the descent of the forearm-dumbbell system) was calculated using inverse dynamics –. The torque of the forearm-hand lever is calculated using the measured distance between the fulcrum of the elbow joint and the center of gravity of the forearm (d_a), the styloid process of the radius (d_{wr}), the center of gravity of the hand (d_h), the center of gravity of the weight (d_w), the weight of the participant (to calculate the mass of the forearm and mass of the hand) and the weight utilized during the overload eccentric repetition (formulas shown in appendix E).

2.8 Data Processing and Reduction

Each participant performed a total of 3 repetitions with maximal resistance against each of the weight conditions. All fifteen repetitions for each participant started at an angle smaller than 90^o of elbow flexion (when the forearm is parallel to the ground) and even though the test administrator aimed at starting all participants' repetitions from an angle of no less than 60^o of elbow flexion and to finish repetitions at around 150^o of elbow flexion at times that was not possible due to the size of the dumbbell plates which got too close to some participants' chest or chin, forcing some participants to initiate their repetitions at angles higher than 60^o.

In order to determine amplitude of activation, the raw data (volts) were converted to Mean EMG (the average of absolute values of the EMG voltages across a specified time period) using Matlab V.7.3.0 (MathWorks, MA, USA) and expressed as normalized to the peak isometric activation.

Custom scripts for MatLab (V.7.3.0) were developed so as to enable the manual selection of the point where the forearm-dumbbell system started to descend – based on the increase of the absolute angular velocity of the forearm-dumbbell system. The selection of the end-point of the trajectory of the forearm-dumbbell system was based on the point where angular velocity changed from negative to positive, signifying the change in direction of the movement of the forearm-dumbbell system.

Following this primary selection of the initial range of motion, values for the following variables were collected only from 80^{o} through 100^{o} of elbow flexion: peak torque, angular velocity at peak torque, power, impulse, average angular velocity, angle at peak torque. Participants who started their repetitions at angles higher than 80^{o} and/or ended repetitions at angles lower than 100^{o} did not generate usable data for the variables above.

Mean EMG was analyzed at different windows of elbow flexion for some participants. If participants did not have valid EMG data within the window of 80^{o} through 100^{o} of elbow flexion, the starting and ending angles were modified to change the window so that valid data could be generated for analysis. It is important to note that the window for EMG data never exceeded a maximum of 20^{o}.

2.9 Statistical Analysis

Peak torque, mean EMG, normalized mean EMG, average angular velocity, torque at 90^{o} and peak torque as a percentage of calculated maximal isometric torque were compared by one-way repeated measures ANOVA. Peak torque and mean EMG were analyzed using six levels representing each condition: isometric, 120%, 140%, 150%, 160% and 170% of concentric 1RM. Normalized mean EMG was analyzed with five levels: 120%, 140%, 150%, 160% and 170% of concentric 1RM. A priori pairwise analysis was performed as well as Bonferroni post hoc test to adjust for multiple comparisons. Both unadjusted and adjusted results are reported for interpretation.

Variables with significant violations of normality or sphericity violations (angular velocity at peak torque, impulse and angle at peak torque) were analyzed through Friedman's ANOVA by ranks, with five levels for condition: 120%, 140%, 150%, 160% and 170% of concentric 1RM. All values were expressed as means ± standard deviation.

All statistical analyses were performed using IBM SPSS Version 20.0 for Windows (NY, USA) and significance was set at $p<0.05$ for all tests, except where a Bonferroni correction was applied to protect against Type I error.

Chapter 3

Results

3.1 Participants and Valid n

A total of 18 participants were included in the analysis, with a mean age of 25.5±5.1 years, height of 1.80±0.57 m, weight of 82.5±11.3 kg, 1RM of 22.6±3.5 kg, and ratio of 1RM to body weight of 27.6±3.9%. Since seventeen participants were right handed and one participant was left handed, handedness score showed a skewed distribution; however, this abnormality had no effect on the other variables of interest and therefore was not transformed.

Participant 9 was excluded from the entire data analysis because the angular velocity for all his repetitions was so high it seemed he was not “resisting the weight”. Participant 23 was excluded from the entire data analysis because his start angle was higher than 85^o and he was presenting abnormally high torque at angles above 100^o, skewing his torque curves, and leading to suspicion that the electrogoniometer may have moved during testing.

Valid number of participants for different variables varied from 7 (power, impulse) through 15 (peak torque, angular velocity at peak torque, average angular velocity, angle at peak torque, torque at 90 degrees and normalized peak torque) because some participants did not have valid data collected from 80^o to 100^o of elbow flexion – the range of motion through which all variables were analyzed – resulting in a number of participants lower than 18 for all variables.

3.2 Peak Torque

The repeated measures ANOVA for peak torque revealed a significant condition effect, $F(5,70)=10.64$, $p<0.05$. Unadjusted pairwise comparison showed isometric peak torque was significantly higher than peak torque at all other conditions. Peak torque at 160% was significantly higher than peak torque at 120% (p<0.05). After Bonferroni adjustment for multiple comparisons, isometric peak torque remained significantly lower than torque at all other conditions (p<0.05) but no other significant differences were noticed between eccentric conditions. The highest peak torque was evident during the 160% condition (108.2 ± 21.5Nm).

Figure 3.1 shows the peak torque across different percentages of concentric 1RM. Figure 3.2 and 3.3 show the variation of torque over different angles of elbow joint angle. Figure 3.2 shows the highest peak torque recorded during the study – participant 16 at 170% concentric 1RM and figure 3.3 shows lowest torque recorded during the study – participant 12 also at 170% concentric 1RM. Mean values for peak torque are shown in table 3.1 on page 33.

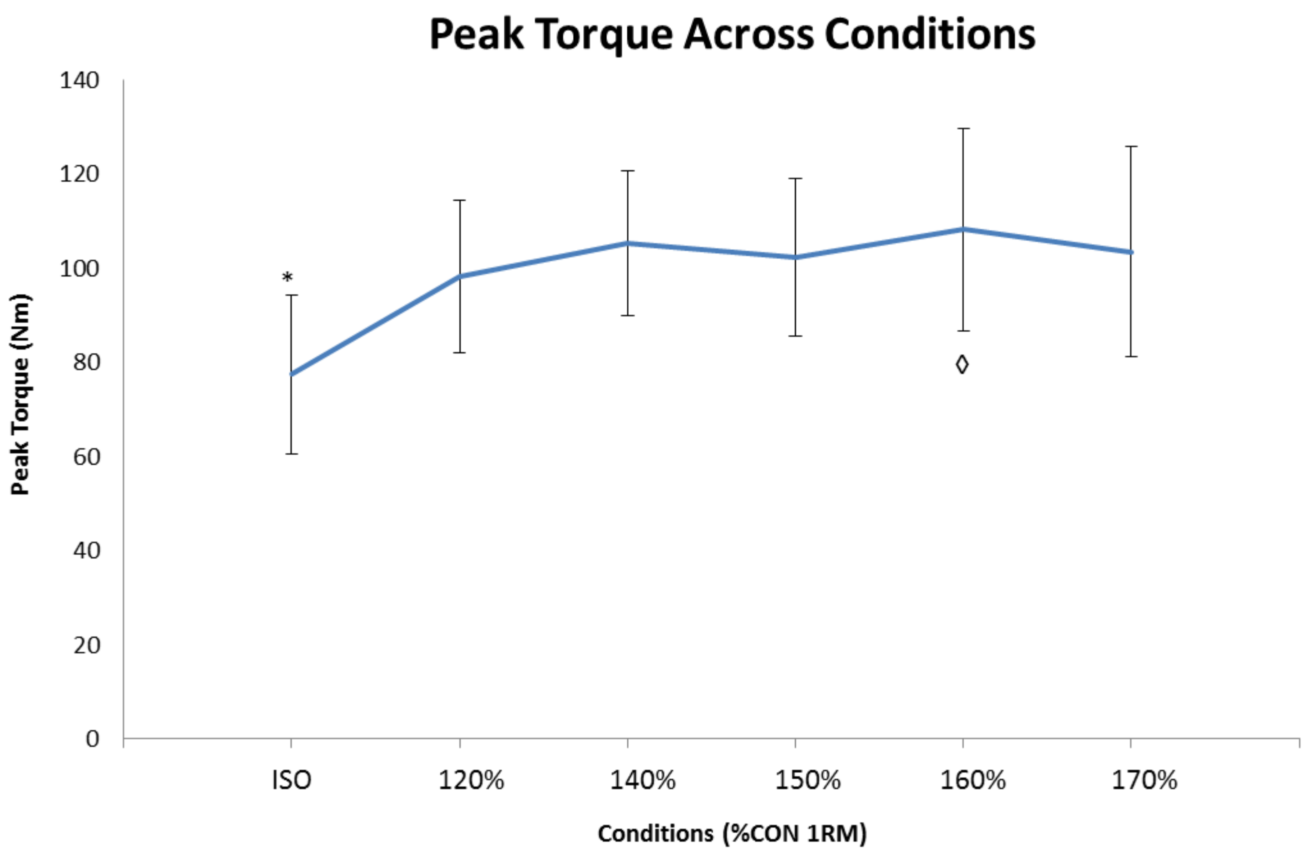

Figure 3.1 – Peak Torque. Values are expressed as means ± standard deviation.
* Peak isometric torque is significantly different than all other conditions (p<0.05).
◊ Peak torque is significantly different than 120%, unadjusted for multiple comparisons (p<0.05).

Torque X Angle of Elbow Joint for Participant 16

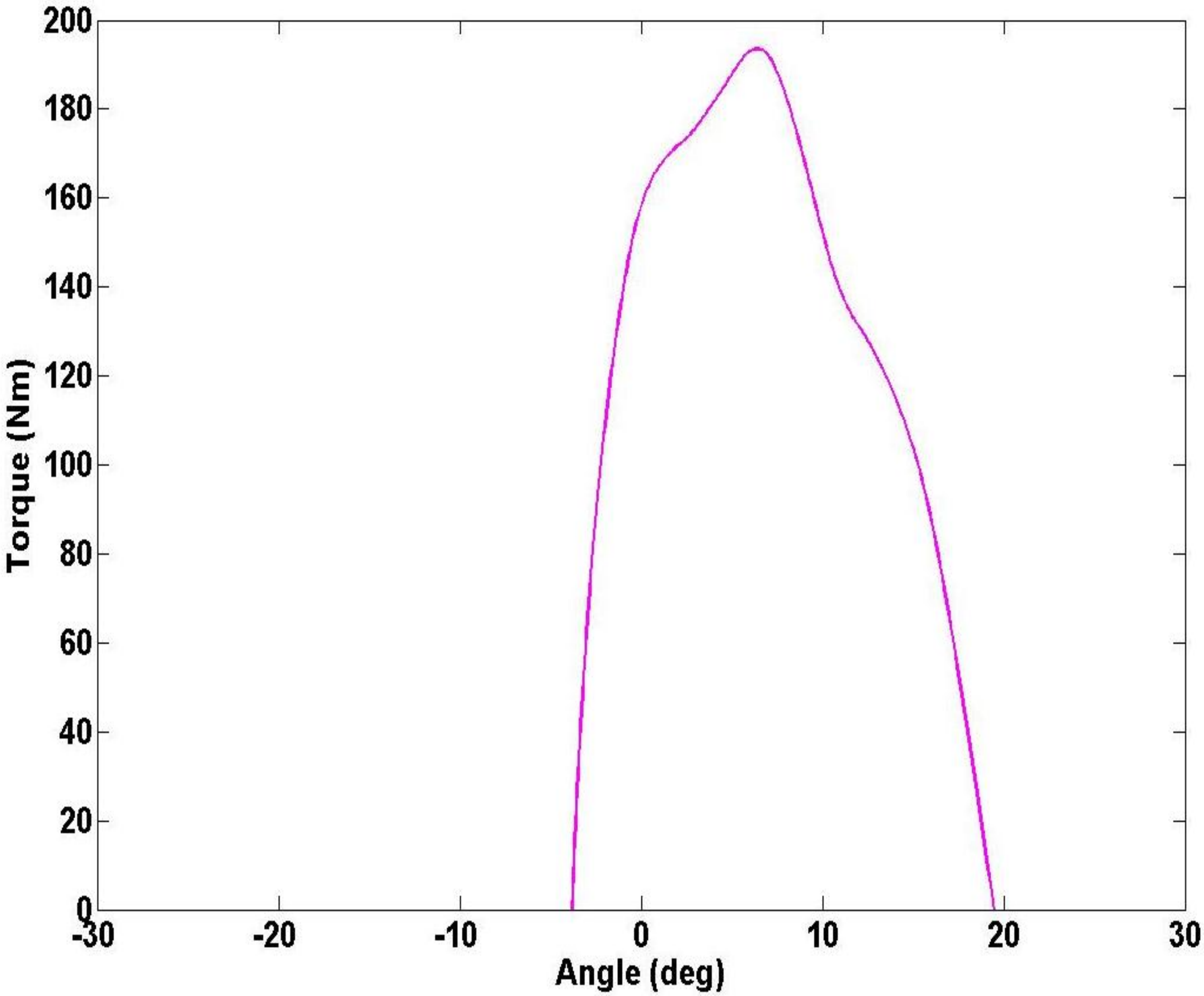

Figure 3.2 – Torque X Angle of Elbow Joint (participant 16)
Representative graph showing the highest torque recorded during the study; participant # 16, under 170% CON 1RM. Note: Angle of 0 = 90° of elbow extension.

Torque X Angle of Elbow Joint for Participant 12

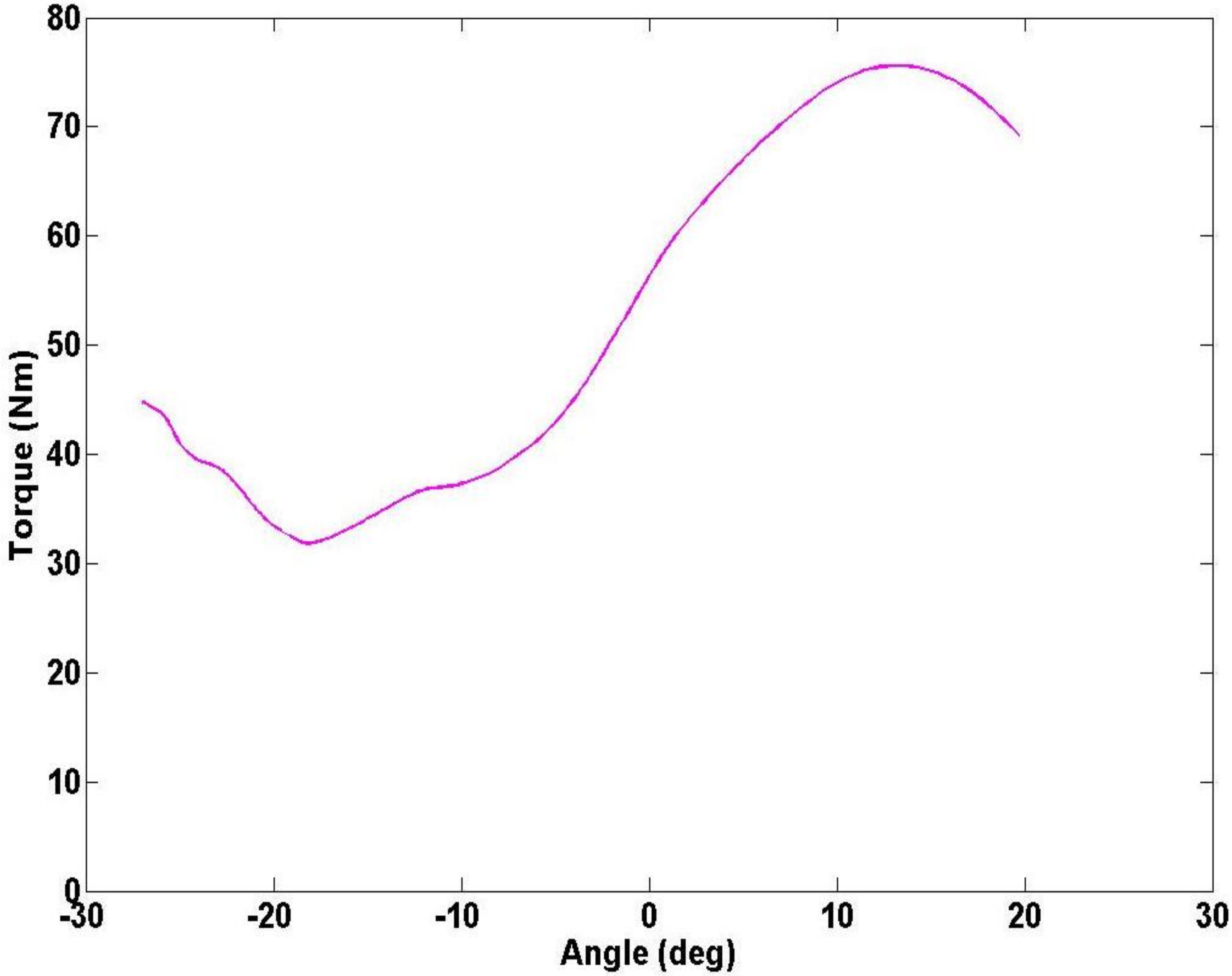

Figure 3.3 – Torque X Angle of Elbow Joint (participant 12)
Representative graph showing the lowest peak torque recorded during the study; participant # 12, under 170% CON 1RM. Note: Angle of 0 = 90°.

Table 3.1 – Means and Standard Deviations of Variables of Interest

Variable	Condition					
	Isometric	**120%**	**140%**	**150%**	**160%**	**170%**
Peak Torque (Nm) n=15	77.4 ± 16.8	98.1 ± 16.2	105.3 ± 15.3	102.3 ± 16.8	108.2 ± 21.5	103.5 ± 22.2
Angular Velocity at Peak Torque (^{o}/s) n=10	--	-65.3 ± 40.8	-104.4 ± 36.4	-133.1 ± 52.1	-128.6 ± 59.0	-162.1 ± 75.2
Mean EMG (mV) n=11	0.792 ± 0.285	0.654 ± 0.313	0.601 ± 0.306	0.533 ± 0.259	0.584 ± 0.299	0.566 ± 0.280
Mean EMG Normalized to Isometric EMG (%) n=11	--	80.1 ± 33.1	74.2 ± 37.4	65.8 ± 28.8	70.2 ± 25.6	69.0 ± 24.5
Power (W) n=7	--	79.8 ± 66.8	166.1 ± 85.7	231.1 ± 87.0	228.8 ± 125.0	265.8 ± 111.3
Impulse (Nms) n=7	--	56.1 ± 54.6	20.6 ± 11.8	13.7 ± 5.2	15.2 ± 8.3	9.6 ± 3.8
Average Angular Velocity (^{o}/s) n=15	--	48.8 ± 25.8	85.3 ± 26.5	109.2 ± 18.5	113.1 ± 30.5	126.6 ± 30.3
Angle at Peak Torque (above 90^o) n=15	--	1.6 ± 2.2	1.3 ± 1.6	1.8 ± 2.9	0.48 ± 2.0	1.8 ± 2.2
Torque at 90 Degrees (Nm) n=15	--	97.0 ± 16.0	100.5 ± 15.3	100.4 ± 17.1	108.3 ± 24.3	101.3 ± 25.7
Calculated Maximal Isometric Torque (Nm) n=15	--	93.5 ± 15.0	104.5 ± 14.7	116.1 ± 18.7	123.6 ± 19.9	129.6 ± 21.6
Peak Torque as a Percentage of Calculated Maximal Isometric Torque (%) n=15	--	106.8 ± 8.7	100.4 ± 12.1	90.4 ± 12.3	88.7 ± 13.8	82.5 ± 16.3

3.3 Angular Velocity at Peak Torque

For angular velocity at peak torque, Mauchly's test showed the assumption of sphericity had been violated; therefore, a non-parametric test was used. Friedman's ANOVA showed statistically significant differences in angular velocity at peak between conditions, $\chi^2(4)=29.71$, $p<0.001$. According to Wilcoxon's two-sample t-tests, there was a statistically significant difference of angular velocity at peak torque (unadjusted for multiple comparisons) between 120% and all other conditions, between 140% and 150%, between 140% and 170%, between 170% and 150% and between 170% and 160% ($p<0.05$). With a Bonferroni-adjustment for multiple comparisons (0.05/10), there was a statistically significant difference between 120% and all other conditions ($p<0.005$).

Angular velocity at peak torque during the 120% condition was 65.3 ± 40.8^{o}/s and rose to 162.1 ± 75.2^{o}/s during the 170% condition. Lowest angular velocity recorded at peak torque was 13.8^{o}/s during the 120% condition and the highest was 310.7^{o}/s during the 170%. Mean values for angular velocity are shown in table 3.1 on page 33.

Figure 3.4 shows the variation of angular velocity across different conditions. Figure 3.5 shows the torque-velocity relationship for participant 16, who generated the highest torque recorded during the study (170.7Nm).

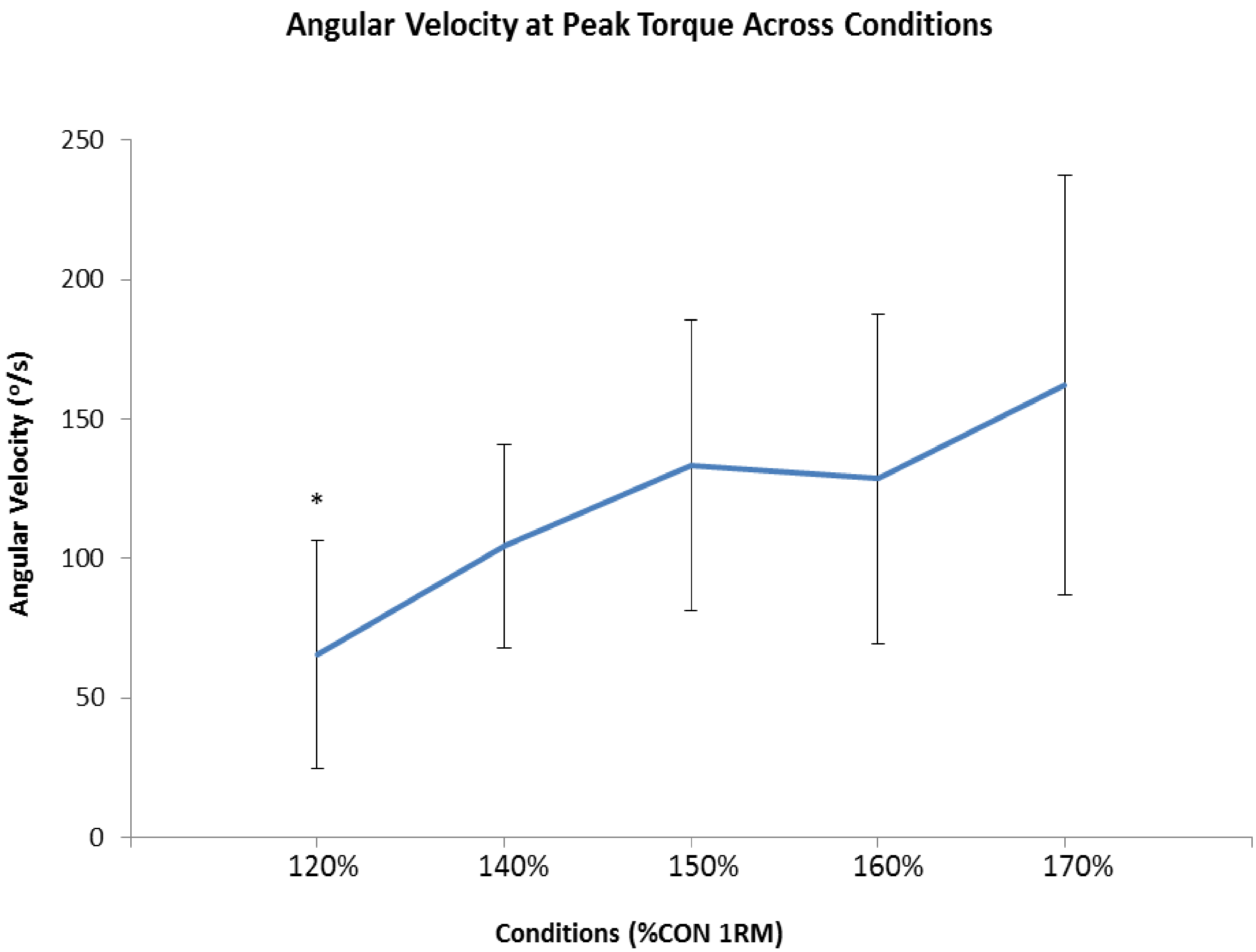

Figure 3.4 – Angular Velocity at Peak Torque. Values are expressed as means ± standard deviation.* Angular velocity at peak torque is significantly lower at 120% than at all other conditions, adjusted for multiple comparisons (p<0.05).

Torque X Velocity Relationship for Participant 16

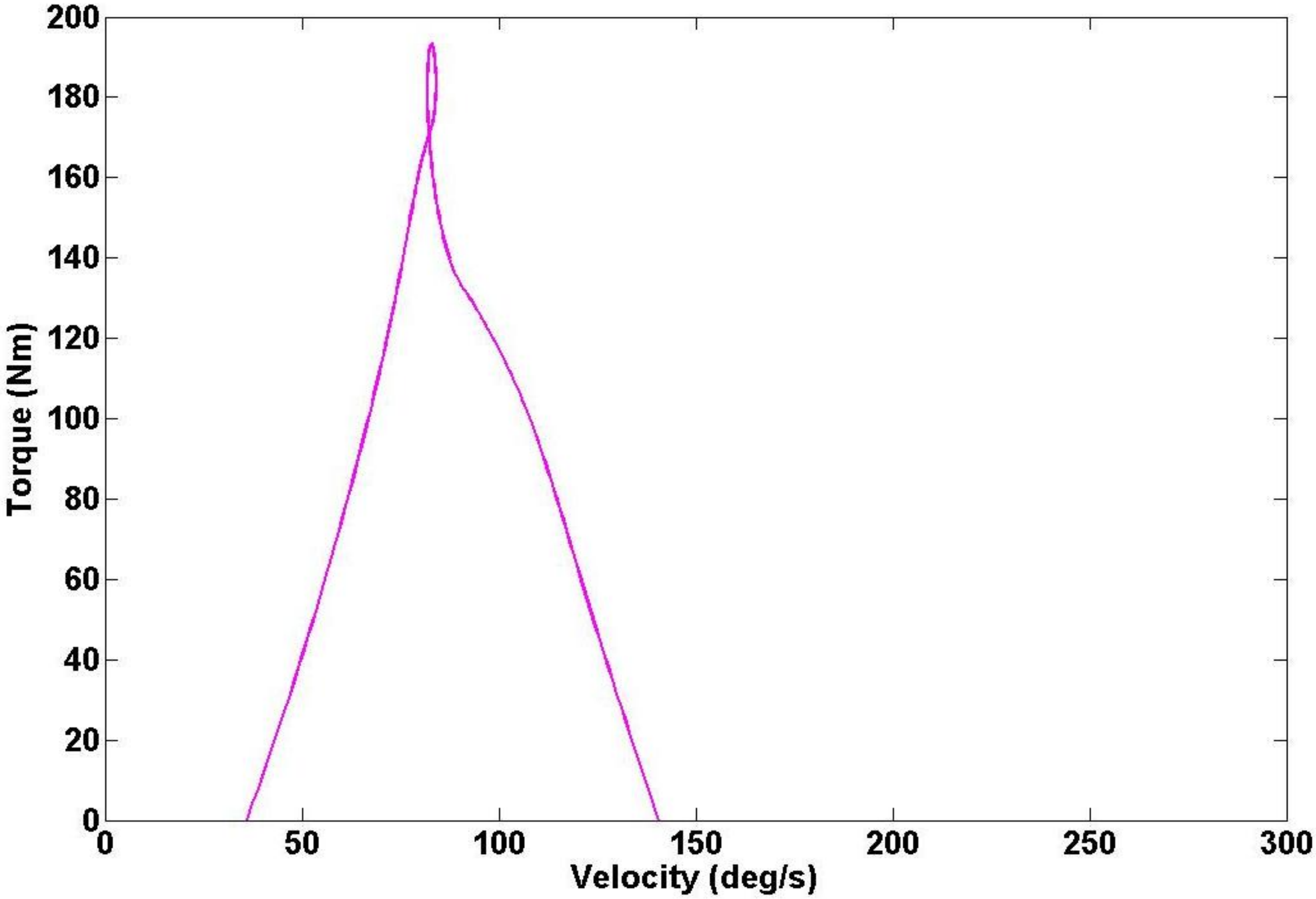

Figure 3.5 – Torque X Velocity Relationship (participant 16)
Representative graph showing the torque-velocity relationship for the highest torque recorded; participant # 16, under 170% CON 1RM.

3.4 Mean EMG

The repeated measures ANOVA for mean EMG revealed significant differences between conditions, $F(5,50)=4.72$, $p<0.05$. Isometric mean EMG was significantly lower than mean EMG at 140%, 150%, 160% and 170% ($p<0.05$) when unadjusted for multiple comparisons. With Bonferroni adjustment, there were no significant differences between any of the conditions. There was a constant reduction of mean EMG throughout the conditions, from the isometric condition (0.792±0.285mV) through the 170% condition (0.566±0.280mV), with no differences between eccentric conditions. Figure 3.6 shows the variation of EMG across different conditions. Mean values for mean EMG are shown in table 3.1 on page 33.

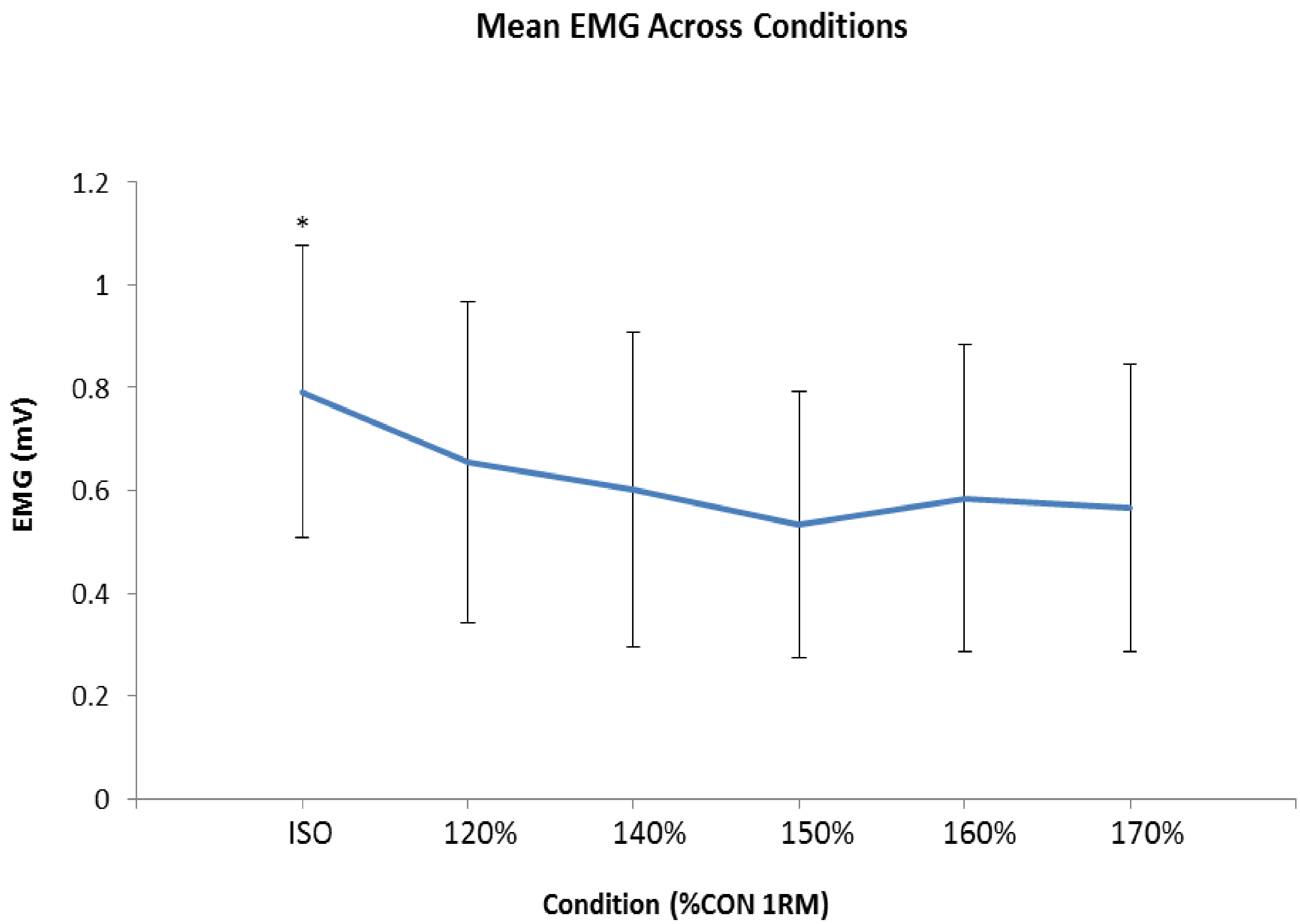

Figure 3.6 – Mean EMG. Values are expressed as means ± standard deviation.
* Mean isometric EMG is significantly different than mean EMG at 140%, 150%, 160% and 170%, unadjusted for multiple comparisons ($p<0.05$).

3.5 Mean EMG Normalized to Isometric EMG

The repeated measures ANOVA showed there were no significant differences in normalized mean EMG between conditions, $F(4,40)=1.41$, $p>0.05$. Mean EMG normalized to isometric EMG across conditions is displayed on table 3.1on page 33.

3.6 Power

Despite the low number of valid data points for this variable (n=7), a repeated measures ANOVA revealed significant differences in power between conditions, $F(4,24)=12.31$, $p<0.001$. The ANOVA showed a statistically significant difference between power at 120% and all other conditions and between 140% and 170% when unadjusted for multiple comparisons ($p<0.05$). With a Bonferroni-adjusted p value for multiple comparisons, there was statistically significant difference between 120% and all other conditions ($p<0.05$).

Power was lowest at the 120% condition (79.9±66.8W) and increased by 333% for the 170% condition (265.8±111.3W; $p<0.05$). Figure 3.7 shows the variation in power across different conditions. Values for power are displayed on table 3.1 on page 33.

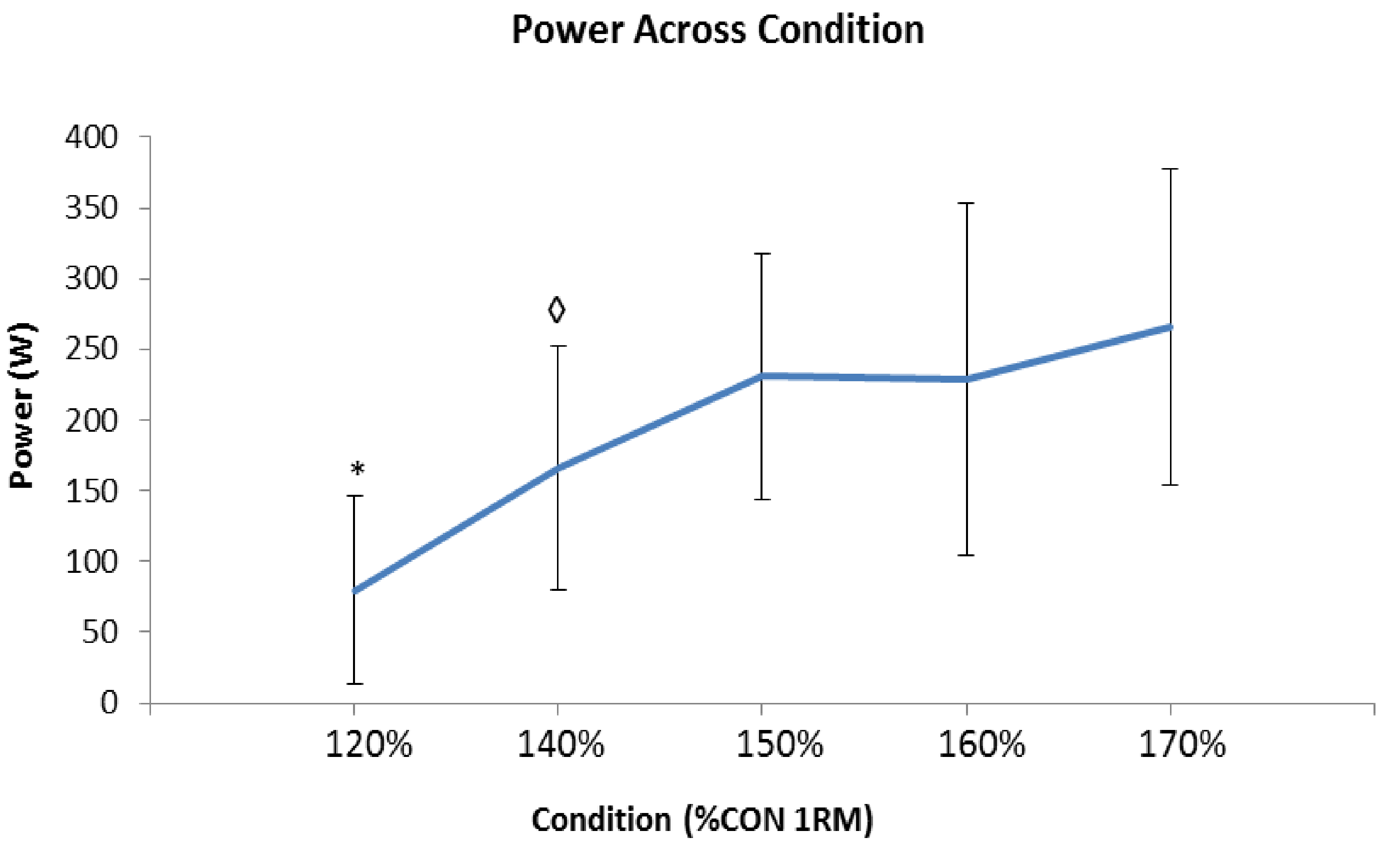

Figure 3.7 – Power. Values are expressed as means ± standard deviation.
* 120% is significantly different than all other conditions (p<0.05).
◊ 140% is significantly different than 170%, unadjusted for multiple comparisons (p<0.05).

3.7 Impulse

For the variable impulse, there were only 7 valid cases and Mauchly's test showed a severe violation of the assumption of sphericity; therefore, a non-parametric approach was used. Friedman's ANOVA showed a statistically significant difference between conditions, $\chi^2(4)=18.06$, $p<0.005$. Wilcoxon non-parametric test showed a statistically significant difference between impulse at 120% and all other conditions ($p<0.05$), and between 140% and 170% when unadjusted for multiple comparisons ($p<0.05$). After Bonferroni adjustment, there were no statistically significant differences between any conditions ($p>0.005$).

Average values of angular impulse ranged from 56.1±54.6 Nms at 120% to 9.6±3.78 Nms at 170% with lowest value of 4.6Nms at 170% and highest value of 172.7Nms at 120%. Figure 3.8 shows the variation in angular impulse across different conditions. Values for impulse are displayed on table 3.1 on page 33.

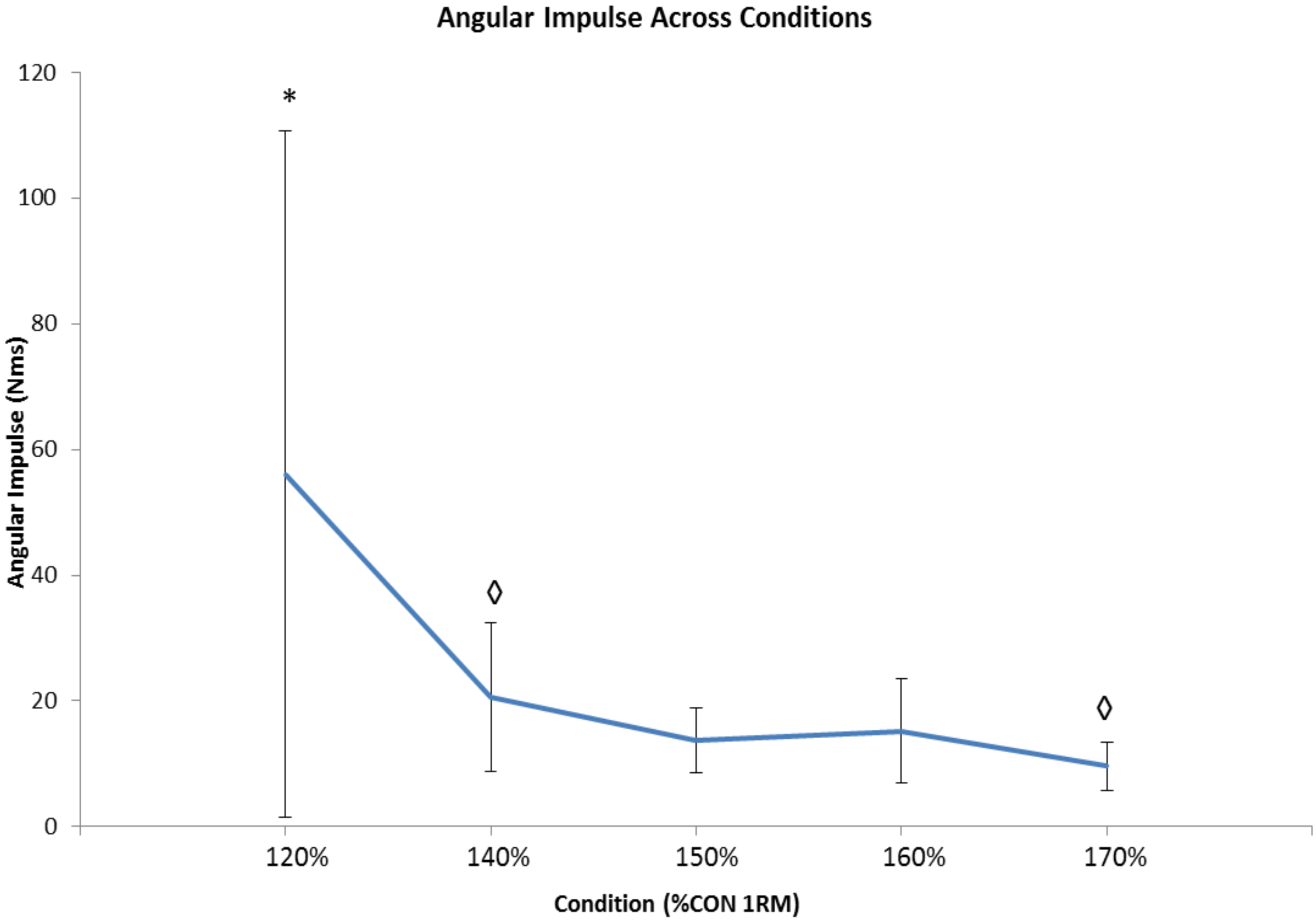

Figure 3.8 – Angular Impulse. Values are expressed as means ± standard deviation.
* Angular impulse is significantly higher at 120% than at all other conditions when unadjusted for multiple comparisons (p<0.05).
◊ Angular impulse is significantly higher at 140% than at 170% when unadjusted for multiple comparisons (p<0.05).

3.8 Average Angular Velocity

The repeated measures ANOVA for average angular velocity revealed significant differences between conditions, $F(4,56) = 42.03$, $p<0.05$. Unadjusted pairwise comparisons showed 120% was significantly different from all other conditions; 140% was different from 150%, 160% and 170%; 150% was different from 170%; 160% was different from 170% ($p<0.05$). Bonferroni-adjusted pairwise comparisons showed 120% was different from all other conditions; 140% was different from 170%; 150% was different from 170% and 160% was different from 170% ($p<0.05$). Average angular velocity ranged from 48.2 ± 26.7^{o}/s at 120% to 134.6 ± 25.8^{o}/s at 170%. Figure 3.9 shows the variation in average angular velocity across conditions. Mean values for average angular velocity are shown in table 3.1 on page 33.

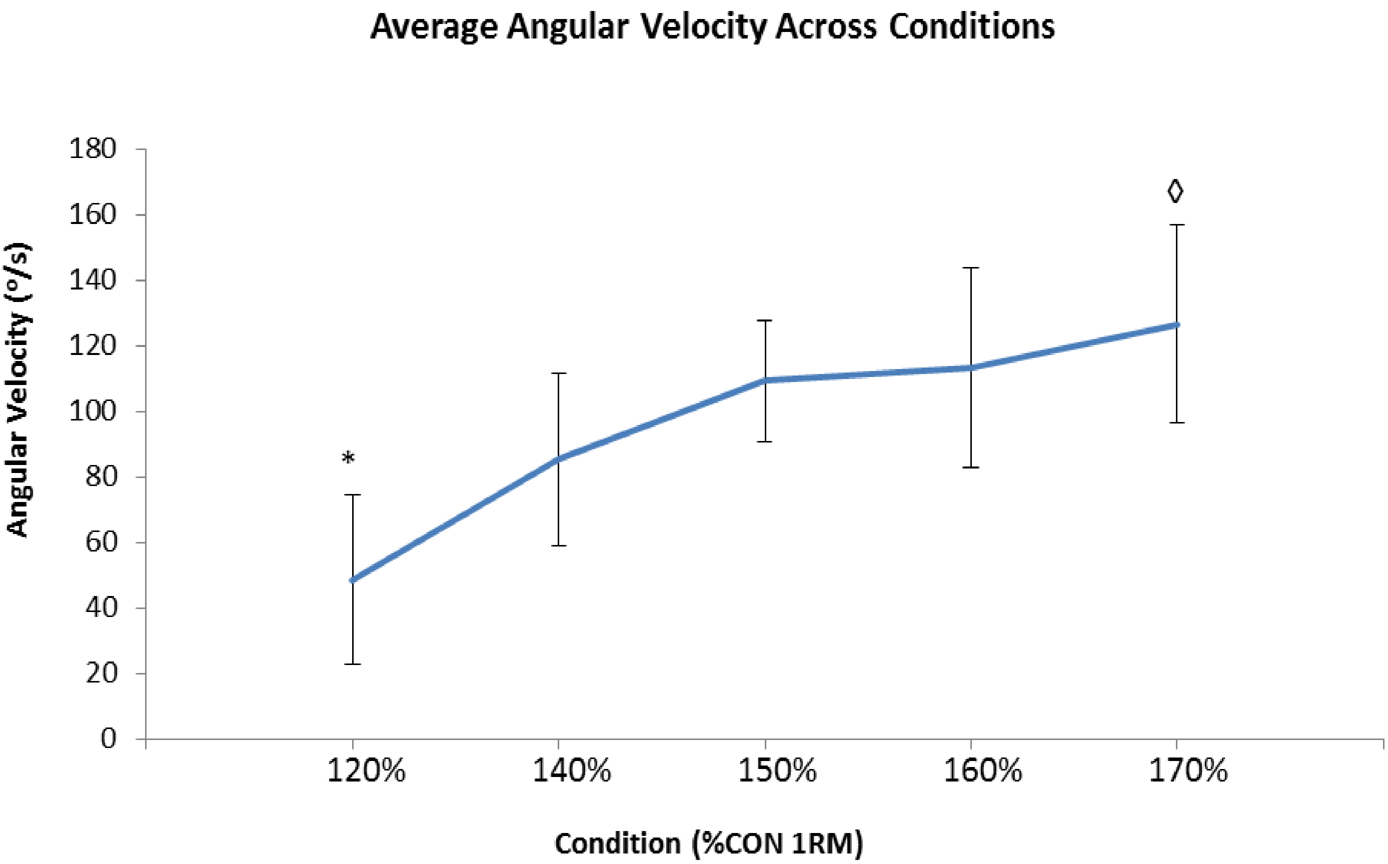

Figure 3.9 – Average Angular Velocity. Values are expressed as means ± standard deviation.
* Average angular velocity was significantly lower than all other conditions (p<0.05).
◊ Average angular velocity was significantly higher than all other conditions (p<0.05).

3.9 Angle at Peak Torque

Angle at peak torque showed violation of normality. Non-parametric Friedman's ANOVA was not significant, $\chi^2(4)=5.17$, $p>0.270$. Table 3.2 below shows the angles at which the highest torques recorded during the study were achieved for each condition. Notice there is little variation in the angle of peak torque.

Table 3.2 – Highest Torques Recorded and Corresponding Joint Angle

Highest Torques Recorded		
	Angle of Elbow Joint (deg)	**Torque (Nm)**
120%	91.2	139.2
140%	89.7	122.8
150%	86.6	137.8
160%	89.9	157.1
170%	88.3	170.7

3.10 Torque at 90 Degrees

The repeated measures ANOVA for torque at 90^{o} was not significant, $F(4,56)=1.689$, $p>0.05$. Averages of torque at 90^{o} ranged from 95.3±15.8Nm at 120% to 106.6±21.4Nm at 160% with lowest values of 56Nm at 170% and highest of 158Nm at 170%. Means values for torque at 90° are shown in table 3.1 on page 33.

3.11 Peak Torque as a Percentage of Calculated Maximal Isometric Torque

The repeated measures ANOVA for peak torque as a percentage of calculated maximal isometric torque was significant; $F(4,56)=12.60$, $p<0.001$. Unadjusted pairwise comparisons showed 120% was significantly different from all other conditions, 140% was significantly different from higher conditions, and 150% was significantly different from 170% ($p<0.05$). After Bonferroni adjustment for multiple comparisons, there are no significant differences between conditions. Peak torques as percentage of calculated maximal isometric torque across conditions are displayed in Figure 3.10.

Average values ranged between 82.5±16.3% of calculated maximal isometric torque during the 170% condition to 106.8±8.7 % calculated maximal isometric torque during the 120% condition. Calculated maximal isometric torque is the amount of torque the elbow flexors would have to generate in order to stop the forearm-dumbbell system at 90^{o} of elbow flexion. The heavier the dumbbell, the greater this torque should be. Peak torque does increase from 120% until 160% and decreases a slightly at 170%. At 120% participants are able to generate peak torque higher than calculated maximal isometric torque and at 140% peak torque is equal to calculated maximal isometric torque. However, the increase in calculated maximal isometric torque is much greater so the difference between calculated maximal isometric torque and peak torque increases drastically from 150% onward.

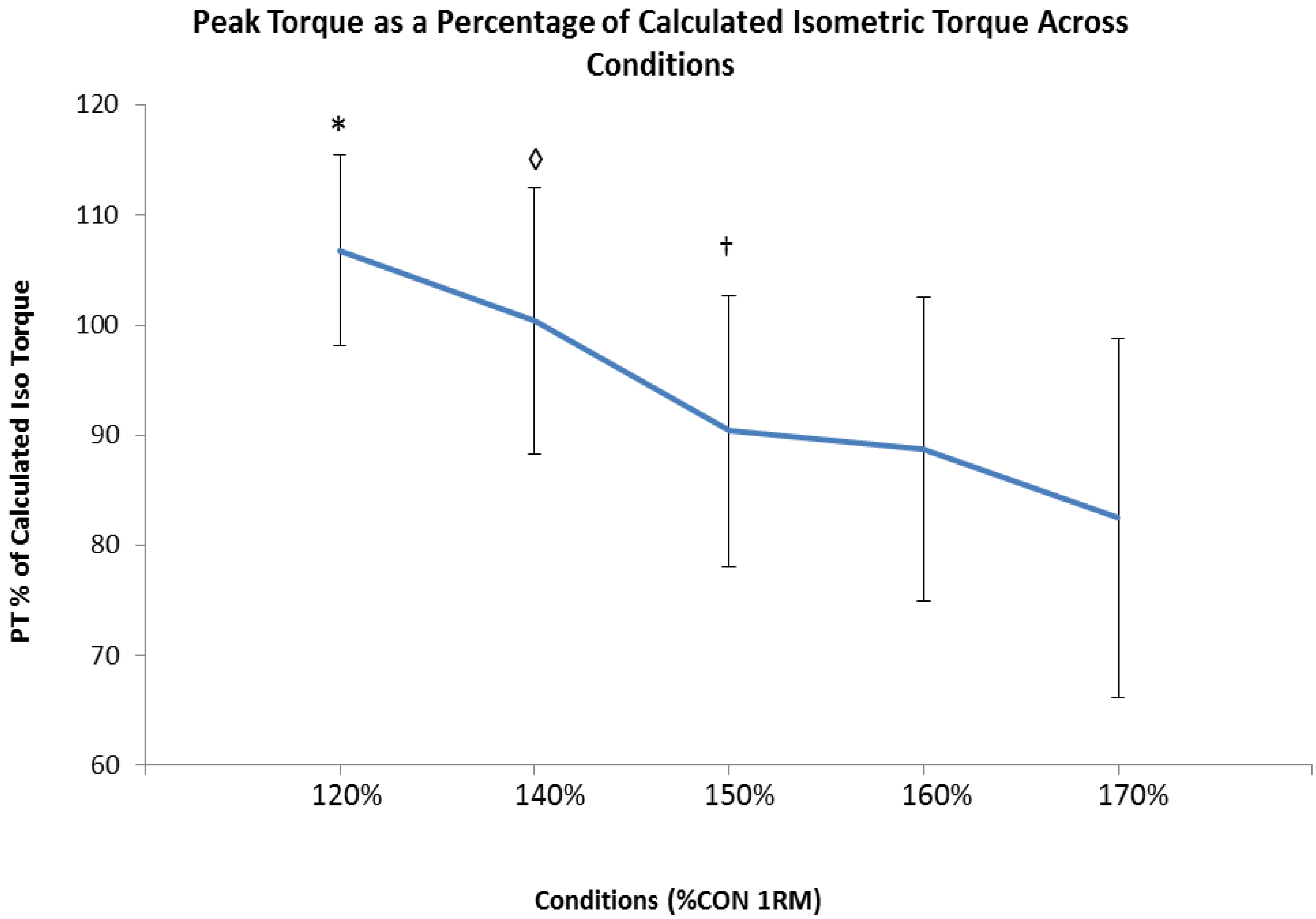

Figure 3.10 – Peak Torque as a Percentage of Calculated Isometric Torque. Values are expressed as means ± standard deviations.

* 120% condition is significantly different than all other conditions, unadjusted for multiple comparisons (p<0.05).

◊ 140% condition is significantly different than higher intensity conditions, unadjusted for multiple comparisons (p<0.05).

† 150% condition is significantly different than 170%, unadjusted for multiple comparisons (p<0.05).

Chapter 4

Discussion

The main findings of this study were that peak torque at all conditions was significantly higher than isometric peak torque and that peak torque at the 160% condition was significantly higher (unadjusted) than peak torque at the 120% condition, supporting the first hypothesis – that peak torque would continue to increase with increasing intensity of eccentric overload. Angular velocity at peak torque was significantly lower during the 120% condition than during all other eccentric conditions and, supporting the second hypothesis, angular velocity at peak torque increased from 120% through 150%, decreased slightly at 160% and rose again at 170%. There was not a significant reduction in EMG from the isometric condition with increasing intensity of eccentric overload; contradicting the third hypothesis that such a reduction in EMG would be a sign of neuromuscular inhibition. Power was significantly greater than 120% for all other eccentric conditions and angular impulse followed the inverse relationship, showing a significant decreased (unadjusted) throughout higher intensities of eccentric overload.

The findings of this study – related to peak torque – are somewhat consistent with existing literature. Jones and Rutherford (1987) suggested that eccentric 1RM of knee flexors lies around 145% of concentric 1RM when assessed on non-athletes and Friedmann-Bette (2010), while assessing athletes who practiced sports where explosive movements were predominant, found that eccentric 1RM could be as high as 190%. This study demonstrated that peak torque was achieved at 160% of concentric 1RM. However, peak torque at 170% was investigated in only 15 participants (all males) and the drop in average peak torque between 160% and 170% was not significant and intensities of concentric 1RM above 170% were not investigated. Therefore, we are unable to state that eccentric peak torque of elbow flexors is 160% concentric

1RM but, based on the results of this study, there is some evidence that it could be within the range between 150-170% concentric 1RM.

4.1 Peak Torque

Jones and Rutherford (1987) suggested that eccentric 1RM for the quadriceps should be between 145-150% concentric 1RM and Friedman-Bette et al. (2010) mentioned that their participants were able to generate as much as 190% concentric 1RM also for the quadriceps group. The results of the current project suggest that for the elbow flexors, there is minimal change in peak torque from 140% to 170% concentric 1RM. There is marginal evidence to suggest that elbow flexion eccentric 1RM may be at 160% concentric 1RM (108.2 ± 21.5Nm), since it was the only condition to show significantly greater peak torque than 120% ($p<0.05$; unadjusted probability). However, with only a slight drop of 4.3% (n.s.) from 160% to 170% concentric 1RM (103.5 ± 22.2Nm), the data remains somewhat inconclusive.

Higher average angular velocity evident with increasing eccentric load (Figure 3.4) could be a limiting factor to the formation of more and stronger cross-bridges in the elbow flexors, resulting in lower ability to generate higher torques. This could explain why there was no increase in peak torque with intensities of 140% and higher. Besides, Caiozzo (2000) suggests that within the first 1-2% stretch of a muscle there is a drop in force development and, perhaps it is safe to assume that by the time the muscles are able to be fully activated, under higher weights, there is simply not enough time left to generate maximal contractions.

4.2 Angular Velocity at Peak Torque

Angular velocity at peak torque increased about two and a half times between 120% and 170% concentric 1RM (from 65.3 ± 40.8^{o}/s to 162.1 ± 75.2^{o}/s; $p<0.05$) increasing as a direct consequence of the increase in the weight utilized. There is some controversy surrounding the relationship between torque and velocity during eccentric contractions. Caiozzo (2000) suggests that higher angular velocities will allow for generation of higher eccentric forces; Hortobagyi et al. (1990) states that strength level influences one's ability to generate higher torques and that the curve of the torque-velocity relationship for higher strength will differ from lower strength since higher strength will allow for increase in force under higher velocities. On the other hand, Enoka (1996) affirms that changes in velocity have no impact on the maximal force muscles can generate under eccentric contractions. Importantly, the majority of prior evidence on torque-velocity relationships was acquired using isokinetic contractions with gradually increasing velocity, rather than by the method of increasing the load using free weights (as in the current study), where the relationship between eccentric torque and velocity is essentially inverse. For example, the fact that angular velocity at peak torque was not significantly different between 150% and 160%, but both were significantly different than 170% (Figure 3.4) may be due to the fact that the highest peak torque was achieved under the 160% condition and there was no corresponding change in velocity despite increased load. Higher eccentric torque generation by the elbow flexors will result in lower velocity of the forearm-dumbbell system.

4.3 Mean and Normalized EMG

Mean EMG was not significantly different across conditions when adjusted for multiple comparisons and, as demonstrated by Rosentswieg and Hinson (1972), all eccentric conditions were significantly lower than isometric. This lower activation could be a product of peculiar neuromuscular recruitment strategies related to fast eccentric contractions or a consequence of the lack of sufficient time to form sufficient cross-bridges and recruit the musculature to its maximal potential (Enoka, 1996). The fact that muscle activation was fairly consistent across the eccentric overload conditions (Figure 3.6) suggests that biceps brachii muscle activation was not the determining factor in generating eccentric torque. The evidence for enhanced peak torque for the 160% condition when compared to the 120% condition was not accompanied with an increase in muscle activation, suggesting factors such as activation of other synergist elbow flexors (e.g. brachialis) or forearm muscles may have been responsible. Another possibility is that there was a lack of statistical power to detect differences in EMG between the eccentric conditions because of high variability and low participant number.

4.4 Power and Impulse

Only seven participants were able to generate usable data on power and impulse to be analyzed, hence it is important to state that the trends observed have very low statistical power. Muscular power – the relationship between angular velocity and torque – was lowest during the 120% condition (79.9±66.8W), and showed little or no change at intensities above 140%. Impulse was greatest during the 120% condition (56.1±54.6 Nms) and was lower for all eccentric conditions with little change with loads higher 140% concentric 1RM.

Power increases in magnitude with increase of eccentric velocity even within a given intensity of concentric 1RM; in this investigation higher weights produced higher eccentric velocities, thus increasing eccentric power for every participant under every condition. Relating all other weight conditions to 120%, power increased 39.1% for the 140% condition, 89.6% for the 150% condition, 86.7% for the 160% condition and the overall increase in power from 120% to 170% (the highest and lowest weight conditions) was of 333.1%. These results suggest that the massive increases in power were heavily dependent on the load-driven, velocity component of power, rather than torque since there were only minimal changes in torque for the eccentric conditions.

Angular impulse followed the reverse relationship with the increase in angular velocity because, for a given weight, impulse increases with increased time under such weight, and with higher weight there was higher angular velocity throughout the range of motion, lowering time under tension for each weight. The overall decrease in impulse between the highest and lowest weight conditions was of 82.9%, which suggests that the much slower time of execution of repetitions with 120% concentric 1RM in relation to those repetitions with 170% concentric 1RM is the predominant factor over the weight utilized when determining angular impulse between these two conditions.

The standard deviation for impulse during the 120% condition was very high because participant 11 was able to control the descent of the weight for 7.132s, achieving an impulse value of 172.7Nms, nearly twice as high as the second highest value (90.6Nms by participant 19) and three times higher than the average impulse for the 120% condition (56.1Nms). However, the data was not transformed because this high impulse was considered a real possibility within the environment because some participants were able to nearly "stop" the weight from lowering. It is difficult to compare the results of this study to others due to an apparent lack of studies that investigate power and impulse under dynamic conditions utilizing free weights.

4.5 Average Angular Velocity

Angular velocity during the 170% condition was significantly higher than that at all other conditions – 11.9% higher than during the 160% condition, 15.9% higher than during the 150% condition, 48.4% higher than during the 140% condition and 159.4% higher than during the 120%. As expected, average angular velocity increased almost linearly throughout conditions as a consequence of the participants' inability to reduce the angular velocity at which the forearm-dumbbell system was lowered. The small decrease in average angular velocity observed during the 160% condition is because the highest peak torque was recorded under this condition; the higher the torque generated, the lower the velocity of descent of the forearm-dumbbell system.

Studies utilizing isokinetic dynamometers at low (30^{o}/s) versus fast (180^{o}/s) eccentric velocities show that greater increases in strength and hypertrophy occur when participants are subject to higher eccentric velocities. The current study was performed utilizing dumbbells (free weights) which induce a constant change in angular velocity throughout the range of motion of the elbow joint and only training studies could determine whether the utilization of different intensities of concentric 1RM can induce different gains in strength and hypertrophy.

4.6 Angle at Peak Torque and Torque at 90 Degrees

Peak torques were achieved at angles of elbow flexion very close to 90^{o}, where the forearm-dumbbell system generates the greatest lever arm, thus, the greater torque. There are very slight differences between the angles where peak torque was achieved and they range from 90.5^{o} for the 160% condition to 91.8^{o} for the 150% and the 170% conditions; however none of these differences were significant. Hortobagyi et al. (1990) suggested that angle at peak torque is similar whether participants are considered to be "stronger" or "weaker"; therefore there is no reason to believe the different levels of strength of the participants had an influence on the angle at peak torques achieved during this study.

These findings contradict the idea that peak eccentric torque is reached with 100^{o} of elbow flexion (Singh and Karpovich, 1966); however, Singh and Karpovich (1966) subjected their participants to an isokinetic condition with constant velocity of 17.4^{o}/s whereas during this study, participants utilized free weights in a gravity dependent environment.

4.7 Peak Torque as a Percentage of Calculated Maximal Isometric Torque

During the 120% condition the average peak torque exceeded the calculated maximal isometric torque (Figure 3.10) – the maximal isometric torque necessary to maintain the forearm-dumbbell system at 90^{o} of elbow flexion – explaining why it is possible for participants to control the descent of the forearm-dumbbell system, generating lower average angular velocities and lower angular velocity at peak torque under this condition. The percentage of peak torque achieved to calculated maximal isometric torque decreases across higher conditions, which explains why average angular velocities increase largely with increasing weights. During the 120% and 140% conditions participants were able to decrease the angular velocity of the forearm-dumbbell system because they were able to generate torques higher than the calculated maximal isometric torque. This high relative torque output even at 90^{o} of elbow flexion (where the forearm-dumbbell system has the greatest mechanical advantage) could be interpreted as an ability to “control the weight”, which is not noticed during the 150% condition and higher conditions.

4.8 Implications and Future Research

This study represents the first attempt to examine the outcomes of the utilization of different intensities of concentric 1RM and how neuromuscular activation changes with increasing intensities. Moreover, this study shows it is safe to utilize intensities as high as 170% of concentric 1RM in the population chosen. This work also demonstrates that elbow flexor muscles can still be activated, are able to generate torques higher than isometric torque and are able to generate eccentric power higher than that generated at 120% concentric 1RM. This information is fundamental when determining whether or not training loads higher than 120% concentric 1RM are deemed “safe” to be utilized in training. Future training studies may aim to demonstrate the feasibility of the utilization of loads higher than 120% concentric 1RM as well as the best number of sets, reps within a set and rest period between sets. There is a clear trade-off between power and impulse with increasing eccentric load, and an important question for future work is to determine the optimal training strategy to meet training goals, whether it is strength, hypertrophy and/or power, while minimizing the risk of muscle damage or injury.

Friedmann-Bette et al. (2010) stated that their participants were able to generate torques – at times – as high as 190% concentric 1RM. This study shows that participants can safely utilize loads as high as 170% concentric 1RM and it may be beneficial to carry out a neuromuscular analysis of elbow flexors at 180% and 190% of concentric 1RM. However, despite the limitation of not testing loads above 170%, there is some marginal evidence from this study – since the results were unadjusted for multiple comparisons – to suggest that eccentric 1RM, for the population investigated, may be around 160% concentric 1RM.

Work-matched training studies are necessary so as to allow for a better understanding not only of which is the best intensity of eccentric overload, but the optimal number of sets, reps within a set and rest period in between sets to induce hypertrophy, gains in strength, power and rate of force development in order to create safe and effective training protocols employing eccentric overload for different populations.

Chapter 5

Summary and Conclusions

5.1 Summary

The main findings of this study are that even moderately trained individuals, when subject to weights equal to170% concentric 1RM are able to generate torques 33.7% higher than isometric torque and power 333% higher than the power generated at 120% concentric 1RM. Mean EMG at 170% concentric 1RM is 28.5% lower than mean isometric EMG and 13.4% lower than mean EMG at 120% concentric 1RM, showing that there is still efficient muscle recruitment at such high intensity of eccentric load.

Peak torque was highest under the 160% condition, suggesting it may not be necessary to utilize 170% concentric 1RM to subject the elbow flexors to maximal torque generation. Average angular impulse across conditions decreased as a result of the continuous increase of average angular velocities – which is a direct consequence of the increased weight across conditions. A drastic decrease of 82.8% in angular impulse between the 120% and 170% conditions leads to the assumption that 170% concentric of 1RM is probably not the best intensity to train when muscle hypertrophy is the primary goal of a training program, in which case 120% concentric 1RM should be the best intensity among the conditions assessed in this work.

5.2 Conclusions

In conclusion, eccentric work for elbow flexors utilizing 150-170% concentric 1RM may be the best choice (among the intensities analyzed in this work) to increase eccentric power and eccentric torque generation without a great reduction in muscle activation. If hypertrophy is the primary goal, then 120% may be the best intensity; however, future training studies are necessary to demonstrate the efficacy of training with intensities higher than 120% concentric 1RM. The 160% intensity was found to be the best intensity to allow for greater power and peak torque generation with minimal drop in EMG.

5.3 Limitations

There are several limitations to this investigation. All participants in this study were males between the ages of 19 and 40, all from the University of Saskatchewan, with moderate weight training history. The results from this study may not be applicable to other populations.

The dumbbells and weight plates utilized did not allow us to adjust the total weight handled by the participants with more sensitivity between conditions. For the majority of the valid repetitions analyzed throughout this work, it was possible to combine the weight plates so as to remain within 0.5lb (227g) of variation in relation to the calculated amount of weight for each weight condition.

The utilization of a custom made electrogoniometer allows for many questions regarding the accuracy of the measurements obtained with this equipment. It is difficult to determine with absolute certainty that the rods of the electrogoniometer are in perfect alignment with the humerus and the radius, thus, reporting the correct angles of elbow flexion at all times. Despite the investigator's diligence in correctly placing the electrogoniometer and his intentions to constantly observe the rods of the electrogoniometer while the participant executed his repetitions and, sometimes, readjust the position of the electrogoniometer in between conditions, there is always the possibility that while the participants contracted their muscles and the forearm moved along its range of motion, the rods may had moved in relation to the humerus and radius.

The participants' ability to unwillingly change and readjust the position of their bodies was a possible source of inaccuracy. Even slight movements of the shoulder joint which changed the optimal position of the humerus (perpendicular to the ground) had the potential to affect the readings of the electrogoniometer, which, in turn, would affect the calculations of all variables of interest. If a participant flexed his shoulders while maintaining 90^o of elbow flexion the moment arm would be smaller even though the goniometer would read the 90^o and torque calculations would yield results higher than the actual values for the real torque being generated by the elbow flexors. Conversely, if a participant extended his shoulder, torque calculations would yield torque values lower than the actual torque generated at the angle read by the electrogoniometer. It is also possible that participants may have moved their thighs medially, pushing the elbow sideways, while contracting the elbow flexors and changed the position of the humerus in relation to the ground, contributing to a possible source of inaccurate readings of the electrogoniometer.

Participants relaxed during the rest period in between conditions, so it is possible that when they repositioned themselves in the concentration curl position they did not return to their original form. However, different body positioning is a possible source of imprecision for any investigation or training that utilizes free weights.

Finally, the size of the weight plates and dumbbell handles affected the ability of some participants to start their repetitions at angles near 60^o since the plates touched their chest at the start angle of some weight conditions.

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Appendices

Appendix A –Certificate of Ethics Approval

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Approval

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Jonathan P. Farthing	Kinesiology	12-192

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
College of Kinesiology
87 Campus Drive
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STUDENT RESEARCHER(S)
Fred Leal

FUNDER(S)
INTERNALLY FUNDED

TITLE
Neuromechanical Analysis of Different Intensities of Overload Eccentric Elbow Flexion

ORIGINAL REVIEW DATE	APPROVED ON	APPROVAL OF	EXPIRY DATE
02-May-2012	17-May-2012	Application for Biomedical Research Ethics Review (Rec'd 24-April-2012) Participant Information and Consent Form v.2 (11-May-2012) Appendix A - Waterloo Handedness Questionnaire (11-May-2012) Appendix B - Concentric 1RM Testing protocol (11-May-2012) Appendix C - Resistance Training Experience & Previous Injury (11-May-2012)	16-May-2013

Delegated Review: ☒ Full Board Meeting: ☐

CERTIFICATION
The study is acceptable on scientific and ethical grounds. The Bio-REB considered the requirements of section 29 under the Health Information Protection Act (HIPA) and is satisfied that this study meets the privacy considerations outlined therein. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face) meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

REB ATTESTATION
In respect to clinical trials, the University of Saskatchewan Research Ethics Board complies with the membership requirements for Research Ethics Boards defined in Part 4 of the Natural Health Products Regulations and Division 5 of the Food and Drug Regulations and carries out its functions in a manner consistent with Good Clinical Practices. Members of the Bio-REB who are named as investigators, do not participate in the discussion related to, nor vote on such studies when presented to the Bio-REB. This approval and the views of this REB have been documented in writing. The University of Saskatchewan Biomedical Research Ethics Board has been

Please send all correspondence to: Research Ethics Office
University of Saskatchewan

PRINCIPAL INVESTIGATOR	- 2 - DEPARTMENT	Bio #
Jonathan P. Farthing	Kinesiology	12-192

approved by the Minister of Health, Province of Saskatchewan, to serve as a Research Ethics Board (REB) for research projects involving human subjects under section 29 of The Health Information Protection Act (HIPA).

Gordon McKay, PhD., Chair
University of Saskatchewan
Biomedical Research Ethics Board

Please send all correspondence to: Research Ethics Office
University of Saskatchewan
Box 5000 RPO University
1607 – 110 Gymnasium Place

UNIVERSITY OF SASKATCHEWAN

Biomedical Research Ethics Board (Bio-REB)

Certificate of Approval
Study Amendment

PRINCIPAL INVESTIGATOR	DEPARTMENT	Bio #
Jonathan P. Farthing	Kinesiology	12-192

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT
College of Kinesiology
87 Campus Drive
Saskatoon SK S7N 5B2

STUDENT RESEARCHER(S)
Fred Leal

FUNDER(S)
INTERNALLY FUNDED

TITLE
Neuromechanical Analysis of Different Intensities of Overload Eccentric Elbow Flexion

APPROVAL OF	APPROVED ON	CURRENT EXPIRY DATE
Revised Participant Information and Consent Form dated 05/10/2012 v3 Revised Application for Biomedical Research Ethics Review with minor change as per email dated 28-Jun-2012, adding one more condition for eccentric reps plus a "free fall" condition.	03-Jul-2012	16-May-2013

Delegated Review ☒ Full Board Meeting ☐

CERTIFICATION
The study is acceptable on scientific and ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research study, and for ensuring that the authorized research is carried out according to governing law. This approval is valid for the specified period provided there is no change to the approved protocol or consent process.

FIRST TIME REVIEW AND CONTINUING APPROVAL
The University of Saskatchewan Biomedical Research Ethics Board reviews above minimal studies at a full-board (face-to-face meeting. Any research classified as minimal risk is reviewed through the delegated (subcommittee) review process. The initial Certificate of Approval includes the approval period the REB has assigned to a study. The Status Report form must be submitted within one month prior to the assigned expiry date. The researcher shall indicate to the REB any specific requirements of the sponsoring organizations (e.g. requirement for full-board review and approval) for the continuing review process deemed necessary for that project. For more information visit http://www.usask.ca/research/ethics_review/.

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G McKay

Gordon McKay, PhD., Chair
University of Saskatchewan
Biomedical Research Ethics Board

Please send all correspondence to:

Research Ethics Office
University of Saskatchewan
Box 5000 RPO University
1607-110 Gymnasium Place
Saskatoon SK S7N 4J8

Appendix B – Consent Form

PARTICIPANT INFORMATION AND CONSENT FORM

STUDY TITLE: Neuromechanical Analysis of Different Intensities of Overload Eccentric Elbow Flexion

PRINCIPAL INVESTIGATOR: Jonathan Farthing, Ph.D., College of Kinesiology, University of Saskatchewan.

SUB-INVESTIGATORS and/or STUDENT RESEARCHERS:; Phil Chilibeck, PhD, College of Kinesiology, University of Saskatchewan; Joel Lanovaz, PhD, College of Kinesiology, University of Saskatchewan, Fred Leal (MSc Candidate), College of Kinesiology, University of Saskatchewan.

SPONSOR [or Funding Agency]

CONTACT PHONE NUMBER: Dr. Jon Farthing: 966-1068 or Fred Leal: 306 341 9230.

INTRODUCTION

You are invited to take part in this research study because we want to investigate if it is possible to determine an eccentric one repetition maximum (1RM) for an eccentric concentration biceps curl.

Eccentric contractions occur when your muscle lengthens during a contraction. For this project an eccentric 1RM is defined as the highest amount of weight that you can lower during a concentration biceps curl before your neuromuscular system "fails" and you stop trying to resist the weight during the eccentric contraction. You have been invited to participate in this study because you have been qualified as a regular weight lifter with at least four weeks of training, free of injuries on your muscles and tendons, you perform biceps curls at least once per week and because you are between 18 and 40 years of age.

Your participation is voluntary. It is up to you to decide whether or not you wish to take part. If you wish to participate, you will be asked to sign this form. If you do decide to take part in this study, you are still free to withdraw at any time and without giving any reasons for your decision.

If you do not wish to participate, this will not affect your employment or academic standing at the University of Saskatchewan to which you are entitled or are presently receiving. It will not affect your relationship with any of the researchers or University of Saskatchewan

Please take time to read the following information carefully. You can ask the researcher to explain any words or information that you do not clearly understand. You may ask as many questions as you need. Please feel free to discuss this with your family, friends or family physician before you decide.

WHY IS THIS STUDY BEING DONE?

This study is being conducted because we want to investigate if it is possible to determine an eccentric 1RM for an eccentric concentration biceps curl, by attempting to measure the point at which your neuromuscular system "fails" and you essentially "drop" the weight.

WHO CAN PARTICIPATE IN THE STUDY? (if applicable)

You are eligible to participate in this study if you are male, between the ages of 18 and 40, with a history of at least 4 weeks of resistance training (that includes biceps curls), healthy and have no reasons to refrain from maximal muscular resistance testing.

WHAT DOES THE STUDY INVOLVE?

If you agree to participate the following will happen:

You will have your weight, height and the distance between your elbow and your wrist measured. After that, we will perform a concentric 1RM test on the concentration curl exercise (a seated elbow flexion exercise) to determine the maximal amount of weight you can lift on this exercise. Based on this 1RM we will calculate 140%, 150%, 160%, 170% of this load and you will be asked to lower these four different weights, always trying your best to resist and not allow the weight to move. During your attempts we will be measuring the angle of your elbow flexion with an electrogoniometer and the amount of muscle activation of your biceps with electromyography equipment (sticky electrodes placed on the skin surface).

The total duration of your commitment to this study will be approximately 2 hrs, which includes two lab visits over 2 days. Your total time commitment will be approximately 2 hours. All testing will be conducted at the University of Saskatchewan (PAC Room 353). If you agree to participate, the following time-line informs you in what you can expect throughout the study.

Day 1

Estimated time – 1 hour

On your first visit to the lab, the researcher(s) will go through the consent form with you and make sure you understand the expectations, risks and benefits associated with the study. You will then be required to sign the consent form before continuing with the study. Afterwards, you fill out a series of questionnaires. This includes a Physical Activity Readiness Questionnaire (PAR-Q), a Waterloo

Handedness Questionnaire (WHQ) and a past upper body injury and exercise experience questionnaire. The purpose of these questionnaires is to determine your dominant arm and make sure that you are used to performing biceps curls and are able to perform maximal strength testing. The questionnaires also help the researchers to screen for anything that may affect your testing results. All testing procedures will be performed on your dominant arm only. After you have completed the questionnaires you will have your height, weight and distance between your elbow and wrist measures and then you will proceed with warm-up and baseline testing. This will consist of:

1) Warm up

You will be required to perform a 5 minute warm up on a stationary bicycle.

2) Concentric 1RM

We will assess the highest amount of weight you can lift with your dominant arm on a concentration curl exercise utilizing the National Strength and Conditioning Association protocol, which consists of:

- warm up with a light resistance that easily allows 5 to 10 repetitions.
- 1-minute rest period.
- Estimate a warm-up load that will allow the athlete to complete three to five repetitions by adding:
    - 10 to 20 pounds (4-9 kg) or 5% to 10%
- 2-minute rest period.
- Estimate a conservative, near-maximal load that will allow the athlete to complete two to three repetitions by adding
    - 10 to 20 pounds (4-9 kg) or 5% to 10%
- 2- to 4-minute rest period
- Make a load increase:

    - 10 to 20 pounds (4-9 kg) or 5% to 10%

- attempt a 1RM.
- If successful, provide a 2- to 4- minute rest period and go back to step 7.
- If failed, provide a 2- to 4- minute rest period, then decrease the load by subtracting 5 to 10 pounds (2-4 kg) or 2.5% to 5% AND then go back to step 8.
- Continue increasing or decreasing the load until the athlete a complete one repetition with proper exercise technique. Ideally, the athlete's 1RM will be measured within three to five testing sets.

3) Muscle Activation

Activation of your elbow flexor muscles will be measured during the strength testing to determine your ability to fully contract your muscles (a technique called electromyography). This is done by placing electrodes (i.e. sticky pads) on your elbow flexor muscles. These electrodes are connected by wires that feed into a device that records the electrical activity in your muscles. In order to make sure the recording signal is accurate your skin will be cleaned with alcohol, and shaved if necessary, prior to putting the electrodes on.

4) Angle of the elbow

During your 1RM test we will have an electrogoniometer attached to your arm and forearm. This equipment is composed of a potentiometer and two metal rods; one rod will be attached to your arm and the other will be attached to your forearm (with Velcro straps) and the part where these rods meet will be placed at your elbow joint. Whenever you flex your elbow we will be able to determine how many degrees your forearm moved in relation to your arm.

Day 2

Estimated time – 1 hour

1) Warm up

You will be required to perform a 5 minute warm up on a stationary bicycle.

2) Eccentric testing

You will be randomly assigned to a specific sequence of the four possible conditions (140%, 150%, 160% and170% 1RM) and you will have, once again, electrogoniometry and electromyography assessed while you perform your maximal effort against each of these weights.

WHAT ARE THE BENEFITS OF PARTICIPATING IN THIS STUDY?

You will have the maximum concentric and eccentric strengths of your elbow flexors measured by a trained exercise specialist. Furthermore, better training protocols could be developed utilizing knowledge gained from this study, which could benefit weight lifters such as you.

ARE THERE POSSIBLE RISKS AND DISCOMFORTS?

If you choose to participate in this study, it is likely that you will experience some discomfort following maximal strength and eccentric exercise testing. It is likely that you will experience muscle soreness after the testing but this should start to decrease within a few days of the testing and disappear completely within one week. A slight risk of muscle injury due to the maximal nature of the test is unavoidable; however this risk will be minimized by a proper warm up and becoming familiar with the devices. There is a small risk of muscle injury or cramping during strength assessment, but this is rare. If an injury occurs first aid will be administered.

If you regularly participate in strength training, you can maintain your regular exercise routine but we ask you to not perform biceps curls for 48 hours prior to your scheduled visits.

WHAT IF NEW INFORMATION BECOMES AVAILABLE THAT MAY AFFECT MY DECISION TO PARTICIPATE?

During the course of this study, new information that may affect your willingness to continue to participate will be provided to you by the researcher.

WHAT HAPPENS IF I DECIDE TO WITHDRAW?

Your participation in this research is entirely voluntary. You may withdraw from this study at any time. If you decide to enter the study and to withdraw at any time in the future, there will be no penalty or loss of benefits to which you are otherwise entitled. Your academic standing and/or employment will not be affected.

If you choose to enter the study and then decide to withdraw later, all data collected about you during your enrolment will be retained for analysis.

WILL I BE INFORMED OF THE RESULTS OF THE STUDY?

The results of the study will be available from Dr. Jon Farthing at the completion of the study. These results will be included as part of a Master's Degree thesis and presentation. Data will be presented in aggregate form. Your name will not be included on any of the data and your identity will remain confidential. You can access the results of this study by contacting Dr. Farthing, Fred Leal, by reading the thesis in electronic format through the ETD (at http://library.usask.ca/etd/) and by attending the presentation of this work during the thesis defense – to be scheduled by the College of Kinesiology.

WHAT WILL THE STUDY COST ME?

You will not be charged for any research-related procedures. You will not be paid for participating in this study. You will not receive any compensation, or financial benefits for being in this study, or as a result of data obtained from research conducted under this study.

WHAT HAPPENS IF SOMETHING GOES WRONG?

In the case of a medical emergency related to the study, you should seek immediate care and, as soon as possible, notify the study doctor. Inform the medical staff you are participating in a clinical study. Necessary medical treatment will be made available at no cost to you. By signing this document, you do not waive any of your legal rights.

WILL MY TAKING PART IN THIS STUDY BE KEPT CONFIDENTIAL?

Your confidentiality will be respected. No information that discloses your identity will be released or published without your specific consent to the disclosure. The testing procedures will take place in an enclosed space in the Physical Activity Complex. Your name will not be attached to any information, nor mentioned in any study report, nor be made available to anyone except the research team. It is the intention of the research team to present the findings to faculty and related workshops, but your identity will not be revealed.

WHO DO I CONTACT IF I HAVE QUESTIONS ABOUT THE STUDY?

If you have any questions or desire further information about this study before or during participation, you can contact Dr. Jon Farthing at 966-1068 or Fred Leal at 306 341 9230.

If you have any concerns about your rights as a research participant and/or your experiences while participating in this study, contact the Chair of the University of Saskatchewan, Biomedical Research Ethics Board at (306) 966-4053. This study has been reviewed and approved on ethical grounds by the University of Saskatchewan, Biomedical Research Ethics Board on July 3rd, 2012.

[Institutional logo/letterhead]

CONSENT TO PARTICIPATE

Study Title: _ Neuromechanical Analysis of Different Intensities of Overload Eccentric Elbow Flexion

____

- I have read (or someone has read to me) the information in this consent form.
- I understand the purpose and procedures and the possible risks and benefits of the study.
- I was given sufficient time to think about it.
- I had the opportunity to ask questions and have received satisfactory answers.
- I understand that I am free to withdraw from this study at any time for any reason and the decision to stop taking part will not affect my future relationships.
- I give permission to the use and disclosure of my de-identified information collected for the research purposes described in this form.
- I understand that by signing this document I do not waive any of my legal rights.
- I will be given a signed copy of this consent form.

I agree to participate in this study:

Printed name of participant: Signature Date

Printed name of person obtaining consent: Signature Date

Appendix C – Resistance Training Experience and Previous Injury Questionnaire

RESISTANCE TRAINING EXPERIENCE & PREVIOUS INJURY

1. If one month of resistance training is considered 3 times per week for 4 weeks, how much resistance training (in months) have you done?
   a. In the previous year? ___________________
   b. In the past month? _____________________

2. If you had previous resistance training experience, did this resistance training include any elbow flexion exercises?

   YES NO

3. Have you ever experienced an injury to your dominant arm?

   YES NO

4. If yes, what was the injury, when did it occur and what was the duration of this condition?

Appendix D – Waterloo Handedness Questionnaire

INSTRUCTIONS: Please indicate your hand preference for the following activities by circling the appropriate response. Think about each question. You might try to imagine yourself performing the task in question. Please take your time.

If you use one hand 95% of the time to perform the described activity, then circle right always or left always as your response.

If you use one hand about 75% of the time, then circle right usually or left usually.

If you use both hands roughly the same amount of time, then circle equally.

1. Which hand do you use for writing?

Left Always Left Usually Equally Right Usually Right Always

2. With which hand would you unscrew a tight jar lid?

Left Always Left Usually Equally Right Usually Right Always

3. In which hand do you hold a toothbrush?

Left Always Left Usually Equally Right Usually Right Always

4. In which hand would you hold a match to strike it?

Left Always　Left Usually　Equally　Right Usually　Right Always

5. Which hand would you use to throw a baseball?

Left Always　Left Usually　Equally　Right Usually　Right Always

6. Which hand do you consider the strongest?

Left Always　Left Usually　Equally　Right Usually　Right Always

7. With which hand would you use a knife to cut bread?

Left Always　Left Usually　Equally　Right Usually　Right Always

8. With which hand do you hold a comb when combing your hair?

Left Always　Left Usually　Equally　Right Usually　Right Always

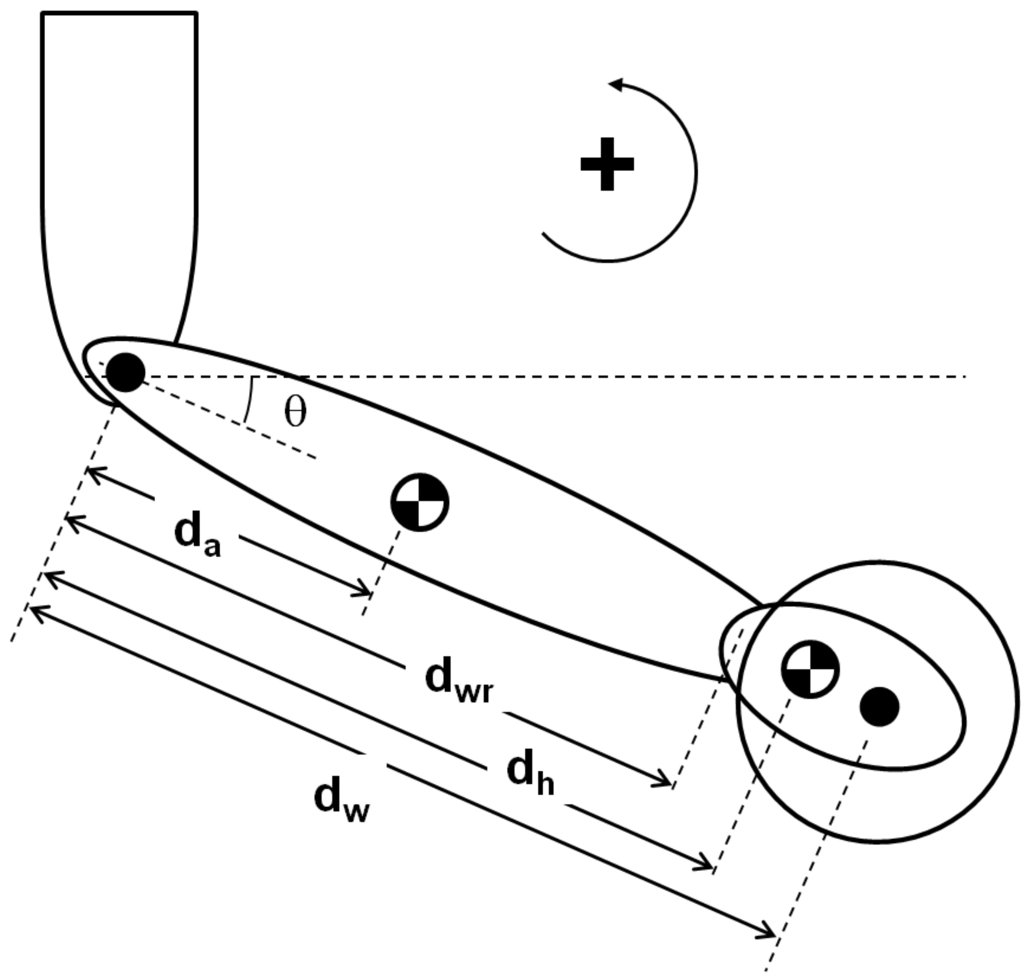
9. Which hand do you use to manipulate implements such as tools?

Left Always　Left Usually　Equally　Right Usually　Right Always

10. Which hand is the most adept to picking up small objects?

Left Always　Left Usually　Equally　Right Usually　Right Always

Appendix E – Elbow Moments Calculation



Variables Measured :

m_{body}	Total body mass
m_w	Mass of the weight
d_{wr}	Distance from elbow to wrist
d_w	Distance from elbow to CG of weight
θ	Angle of forearm from horizontal
g	Gravitational constant (9.81 m/s^2)

Variables Calculated:

m_a	Mass of the forearm
m_h	Mass of the hand
d_a	Distance from elbow to CG of forearm
d_h	Distance from elbow to CG of hand
ω	Angular velocity of forearm
α	Angular acceleration of forearm
I_a	Moment of inertia of forearm wrt to CG
I_{total}	Moment of inertia of forearm/hand/weight wrt to elbow
M_a	Torque due to gravity acting on forearm
M_h	Torque due to gravity acting on hand
M_w	Torque due to gravity acting on weight
$\mathbf{M_{elbow}}$	**Net torque generated by structures around elbow joint**
P_{elbow}	Elbow joint power

The mass of the forearm and hand were estimated from anthropometric tables (de Leva, 1996) based on percentages of total body mass. The locations of centre of mass for the forearm with respect to the elbow and the hand with respect to the wrist were also obtained from the same tables. The location of the combined centre of mass of the forearm, hand and dumbbell was calculated and expressed with respect to the elbow.

The moments of inertia of the forearm and hand with respect to their centres of mass were estimated from anthropometric tables (de Leva, 1996) while the moment of inertia of the dumbbell was estimated from equations for a thin circular cylinder (Meriam and Kraige, 1986). The combined moment of inertia with respect to the elbow for the forearm/hand/dumbbell was then calculated using the parallel axis theorem (Meriam and Kraige, 1986). For all calculations, it was assumed that the forearm/hand/dumbbell acted as a single rigid segment.

Angular position of the forearm (θ) was obtained from the electrogoniometer data and expressed such that $\theta = 0$ degrees when the forearm was parallel to the ground, with a positive angle when the arm was tilted down and a negative angle when the arm was tilted up (see Fig G1). Angular acceleration of the forearm was calculated from the forearm angle data using standard finite difference methods (Winter, 2009).

The elbow was modelled as a frictionless pin joint and the torque component due to the net action of the muscles was calculated using standard inverse dynamics techniques (Winter, 2009). This involves solving the momentum balance around the elbow joint using the equation:

$$M_{muscle} - M_g = I\alpha \qquad \text{(G.1)}$$

where M_{muscle} is the net torque produced by the muscles surrounding the elbow joint, M_g is the torque around the elbow joint due to gravity, I is the moment of inertia of the forearm/hand/dumbbell with respect to the elbow and α is the angular acceleration of the arm (in rad/s^2). Note that if there would be no muscle torque (i.e. $M_{muscle} = 0$), then the measured angular acceleration would be solely due to gravity.

The torque due to gravity was calculated as the sum of the gravitational torques on the forearm, hand and dumbbell:

$$M_g = (d_a m_a + d_h m_h + d_w m_w)\cos(\theta)\, g \qquad \text{(G.2)}$$

For each sample point in a given trial, the forearm angle (θ) and angular acceleration (α) were obtained and the resulting torque due to the muscles around the elbow were calculated using equations G1 and G2.

Once the muscle torque was calculated, the muscle power could also be calculated by multiplying the muscle toque by the angular velocity:

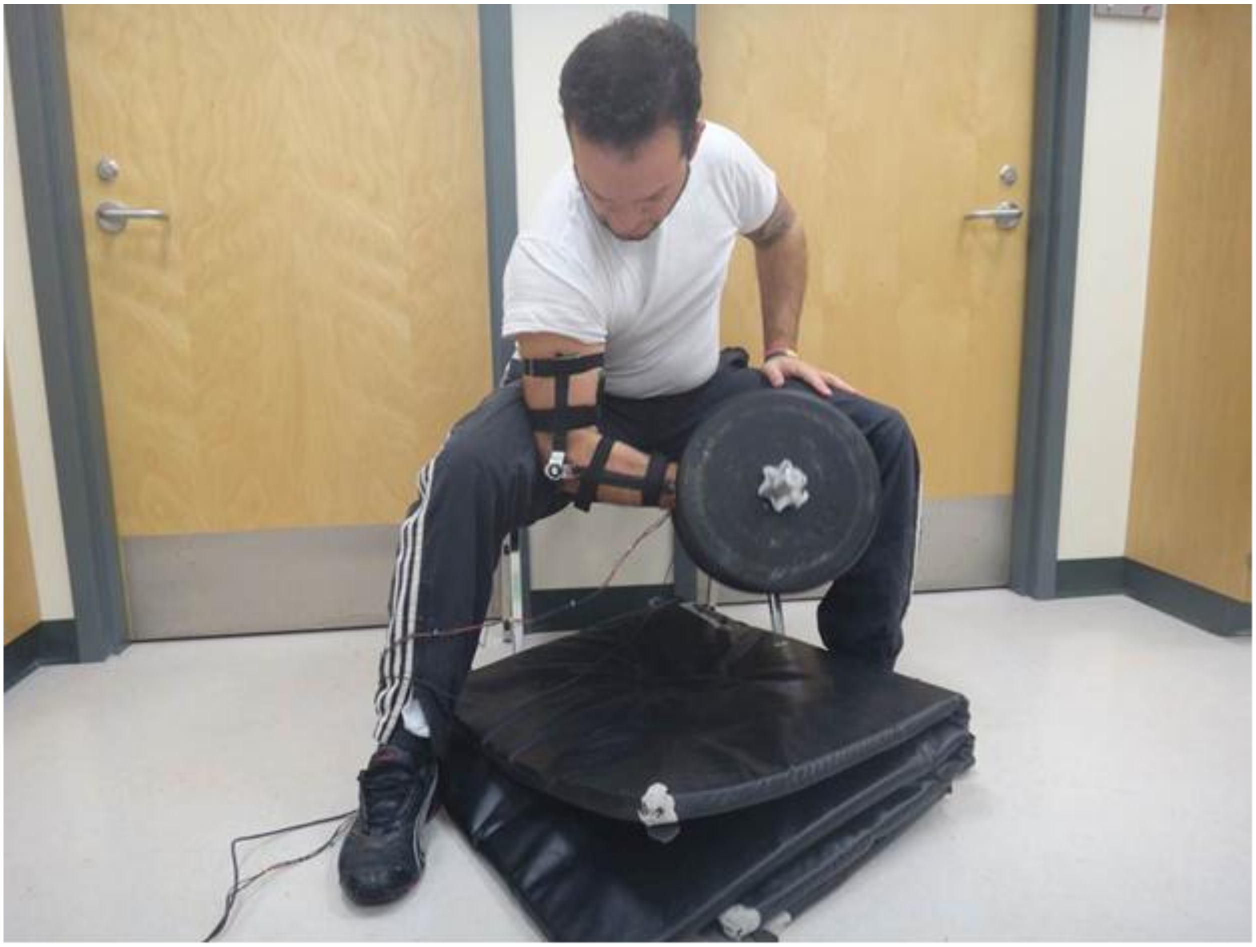
$$P_{elbow} = M_{muscle}\,\omega \qquad \text{(G.3)}$$

where ω is the angular velocity of the forearm calculated from θ using standard finite difference methods (Winter, 2009).

Appendix F – Isometric Peak Torque Assessment

Appendix G – Placement of the Electrogoniometer

Appendix H – Concentration Curl Position



Appendix I - Concentric 1RM Testing Protocol

(National Strength and Conditioning Association, 2008)

1. Instruct the athlete to warm up with a light resistance that easily allows 5 to 10 repetitions.
2. Provide a 1-minute rest period.
3. Estimate a warm-up load that will allow the athlete to complete three to five repetitions by adding:
   - 10 to 20 pounds (4-9 kg) or 5% to 10% for upper body exercise or
   - 30 to 40 pounds (14-18 kg) or 10% to 20% for lower body exercise
4. Provide a 2-minute rest period.
5. Estimate a conservative, near-maximal load that will allow the athlete to complete two to three repetitions by adding
   - 10 to 20 pounds (4-9 kg) or 5% to 10% for upper body exercise or
   - 30 to 40 pounds (14-18 kg) or 10% to 20% for lower body exercise
6. Provide a 2- to 4-minute rest period
7. Make a load increase:
   - 10 to 20 pounds (4-9 kg) or 5% to 10% for upper body exercise or
   - 30 to 40 pounds (14-18 kg) or 10% to 20% for lower body exercise
8. Instruct the athlete to attempt a 1RM.
9. If the athlete was successful, provide a 2- to 4- minute rest period and go back to step 7.

If the athlete failed, provide a 2- to 4- minute rest period, then decrease the load by subtracting

- 5 to 10 pounds (2-4 kg) or 2.5% to 5% for upper body exercise or
- 15 to 20 pounds (7-9 kg) or 5% to 10% for lower body exercise

AND then go back to step 8.

Continue increasing or decreasing the load until the athlete a complete one repetition with proper exercise technique. Ideally, the athlete’s 1RM will be measured within three to five testing sets.

Appendix J – Order of Load Assignment

Subject	Order of Intensities				
1	120	140	150	160	170
2	140	150	160	170	120
3	150	140	160	170	120
4	160	140	150	170	120
5	170	140	150	160	120
6	120	150	160	170	140
7	140	160	170	120	150
8	150	160	170	120	140
9	160	120	140	150	170
10	170	120	140	150	160
11	120	160	170	140	150
12	140	120	150	160	170
13	150	120	140	160	170
14	160	150	170	120	140
15	170	160	120	140	150
16	120	170	160	120	140
17	140	170	120	150	160
18	150	170	120	140	160
19	160	170	120	140	150
20	170	150	160	120	140

Appendix K –Statistical Tables

1. Participants

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
age	18	19	35	25.50	5.113
height	18	1.6700	1.9200	1.803889	.0565830
weight	18	62.8500	101.2000	82.461111	11.3304841
hand	18	-9	20	14.44	6.679
RM1	18	17.70	30.00	22.5928	3.46026
RM1_BW_perct	18	19.03	35.01	27.6394	3.91610
Valid N (listwise)	18				

2. Peak Torque

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	.251	16.740	14	.279	.714	.989	.200

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	9352.614	5	1870.523	10.644	.000
	Greenhouse-Geisser	9352.614	3.571	2619.211	10.644	.000
	Huynh-Feldt	9352.614	4.944	1891.727	10.644	.000
	Lower-bound	9352.614	1.000	9352.614	10.644	.006
Error(condition)	Sphericity Assumed	12301.782	70	175.740		
	Greenhouse-Geisser	12301.782	49.991	246.081		
	Huynh-Feldt	12301.782	69.215	177.732		
	Lower-bound	12301.782	14.000	878.699		

Unadjusted Pairwise Comparisons

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	-20.761*	5.366	.002	-32.270	-9.253
	3	-27.938*	4.051	.000	-36.626	-19.250
	4	-24.912*	5.136	.000	-35.928	-13.897
	5	-30.818*	5.935	.000	-43.548	-18.089
	6	-26.102*	5.841	.001	-38.629	-13.574
2	1	20.761*	5.366	.002	9.253	32.270
	3	-7.177	3.540	.062	-14.770	.417
	4	-4.151	3.735	.285	-12.162	3.860
	5	-10.057*	4.440	.040	-19.580	-.534
	6	-5.340	5.551	.352	-17.245	6.565
3	1	27.938*	4.051	.000	19.250	36.626
	2	7.177	3.540	.062	-.417	14.770
	4	3.026	4.173	.480	-5.925	11.976
	5	-2.880	4.068	.491	-11.606	5.845
	6	1.837	6.051	.766	-11.142	14.815
4	1	24.912*	5.136	.000	13.897	35.928
	2	4.151	3.735	.285	-3.860	12.162
	3	-3.026	4.173	.480	-11.976	5.925
	5	-5.906	4.550	.215	-15.664	3.852
	6	-1.189	4.465	.794	-10.765	8.386
5	1	30.818*	5.935	.000	18.089	43.548
	2	10.057*	4.440	.040	.534	19.580
	3	2.880	4.068	.491	-5.845	11.606
	4	5.906	4.550	.215	-3.852	15.664
	6	4.717	4.726	.335	-5.419	14.853
6	1	26.102*	5.841	.001	13.574	38.629
	2	5.340	5.551	.352	-6.565	17.245
	3	-1.837	6.051	.766	-14.815	11.142
	4	1.189	4.465	.794	-8.386	10.765
	5	-4.717	4.726	.335	-14.853	5.419

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).

Bonferroni-Adjusted Pairwise Comparisons

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	-20.761*	5.366	.026	-39.701	-1.822
	3	-27.938*	4.051	.000	-42.236	-13.641
	4	-24.912*	5.136	.004	-43.040	-6.785
	5	-30.818*	5.935	.002	-51.767	-9.870
	6	-26.102*	5.841	.008	-46.717	-5.486
2	1	20.761*	5.366	.026	1.822	39.701
	3	-7.177	3.540	.932	-19.673	5.320
	4	-4.151	3.735	1.000	-17.335	9.033
	5	-10.057	4.440	.599	-25.729	5.615
	6	-5.340	5.551	1.000	-24.932	14.252
3	1	27.938*	4.051	.000	13.641	42.236
	2	7.177	3.540	.932	-5.320	19.673
	4	3.026	4.173	1.000	-11.704	17.755
	5	-2.880	4.068	1.000	-17.240	11.479
	6	1.837	6.051	1.000	-19.521	23.195
4	1	24.912*	5.136	.004	6.785	43.040
	2	4.151	3.735	1.000	-9.033	17.335
	3	-3.026	4.173	1.000	-17.755	11.704
	5	-5.906	4.550	1.000	-21.964	10.152
	6	-1.189	4.465	1.000	-16.947	14.569
5	1	30.818*	5.935	.002	9.870	51.767
	2	10.057	4.440	.599	-5.615	25.729
	3	2.880	4.068	1.000	-11.479	17.240
	4	5.906	4.550	1.000	-10.152	21.964
	6	4.717	4.726	1.000	-11.963	21.397
6	1	26.102*	5.841	.008	5.486	46.717
	2	5.340	5.551	1.000	-14.252	24.932
	3	-1.837	6.051	1.000	-23.195	19.521
	4	1.189	4.465	1.000	-14.569	16.947
	5	-4.717	4.726	1.000	-21.397	11.963

Based on estimated marginal means

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

b. Adjustment for multiple comparisons: Bonferroni.

3. Angular Velocity at Peak Torque

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	.132	25.163	9	.003	.480	.555	.250

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.

Test Statistics[a]

	angvel@PT_1 40 - angvel@PT_1 20	angvel@PT_1 50 - angvel@PT_1 20	angvel@PT_1 60 - angvel@PT_1 20	angvel@PT_1 70 - angvel@PT_1 20	angvel@PT_1 50 - angvel@PT_1 40	angvel@PT_1 60 - angvel@PT_1 40	angvel@PT_1 70 - angvel@PT_1 40	angvel@PT_1 60 - angvel@PT_1 50	angvel@PT_1 70 - angvel@PT_1 50	angvel@PT_1 70 - angvel@PT_1 60
Z	-3.010[b]	-3.408[b]	-3.181[b]	-3.294[b]	-2.158[b]	-1.761[b]	-2.613[b]	-.454[c]	-2.442[b]	-2.442[b]
Asymp. Sig. (2-tailed)	.003	.001	.001	.001	.031	.078	.009	.650	.015	.015

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

c. Based on negative ranks.

Test Statistics[a]

N	15
Chi-Square	29.707
df	4
Asymp. Sig.	.000

a. Friedman Test

4. Mean 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
condition	.104	18.314	14	.211	.649	.997	.200

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	.472	5	.094	4.723	.001
	Greenhouse-Geisser	.472	3.245	.145	4.723	.006
	Huynh-Feldt	.472	4.987	.095	4.723	.001
	Lower-bound	.472	1.000	.472	4.723	.055
Error(condition)	Sphericity Assumed	.999	50	.020		
	Greenhouse-Geisser	.999	32.447	.031		
	Huynh-Feldt	.999	49.875	.020		
	Lower-bound	.999	10.000	.100		

Unadjusted Pairwise Comparisons

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	.138	.075	.097	-.030	.306
	3	.191*	.086	.049	.001	.382
	4	.259*	.073	.005	.097	.420
	5	.208*	.056	.004	.082	.334
	6	.226*	.059	.003	.094	.358
2	1	-.138	.075	.097	-.306	.030
	3	.053	.054	.347	-.067	.174
	4	.121	.061	.078	-.016	.258
	5	.070	.038	.097	-.015	.156
	6	.088	.060	.171	-.045	.222
3	1	-.191*	.086	.049	-.382	-.001
	2	-.053	.054	.347	-.174	.067
	4	.067	.058	.268	-.061	.196
	5	.017	.061	.787	-.119	.153
	6	.035	.059	.565	-.096	.166
4	1	-.259*	.073	.005	-.420	-.097
	2	-.121	.061	.078	-.258	.016
	3	-.067	.058	.268	-.196	.061
	5	-.050	.061	.428	-.187	.086
	6	-.032	.047	.505	-.137	.072
5	1	-.208*	.056	.004	-.334	-.082
	2	-.070	.038	.097	-.156	.015
	3	-.017	.061	.787	-.153	.119
	4	.050	.061	.428	-.086	.187
	6	.018	.037	.638	-.065	.101
6	1	-.226*	.059	.003	-.358	-.094
	2	-.088	.060	.171	-.222	.045
	3	-.035	.059	.565	-.166	.096
	4	.032	.047	.505	-.072	.137
	5	-.018	.037	.638	-.101	.065

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).

Bonferroni-Adjusted Pairwise Comparisons

Pairwise Comparisons

Measure: MEASURE_1

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.138	.075	1.000	-.150	.426
	3	.191	.086	.738	-.136	.519
	4	.259	.073	.077	-.019	.536
	5	.208	.056	.063	-.008	.424
	6	.226	.059	.051	.000	.453
2	1	-.138	.075	1.000	-.426	.150
	3	.053	.054	1.000	-.154	.260
	4	.121	.061	1.000	-.114	.356
	5	.070	.038	1.000	-.077	.217
	6	.088	.060	1.000	-.141	.317
3	1	-.191	.086	.738	-.519	.136
	2	-.053	.054	1.000	-.260	.154
	4	.067	.058	1.000	-.153	.287
	5	.017	.061	1.000	-.216	.250
	6	.035	.059	1.000	-.190	.259
4	1	-.259	.073	.077	-.536	.019
	2	-.121	.061	1.000	-.356	.114
	3	-.067	.058	1.000	-.287	.153
	5	-.050	.061	1.000	-.285	.184
	6	-.032	.047	1.000	-.212	.147
5	1	-.208	.056	.063	-.424	.008
	2	-.070	.038	1.000	-.217	.077
	3	-.017	.061	1.000	-.250	.216
	4	.050	.061	1.000	-.184	.285
	6	.018	.037	1.000	-.124	.160
6	1	-.226	.059	.051	-.453	.000
	2	-.088	.060	1.000	-.317	.141
	3	-.035	.059	1.000	-.259	.190
	4	.032	.047	1.000	-.147	.212
	5	-.018	.037	1.000	-.160	.124

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

5. Mean EMG Normalized to Isometric Mean 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
condition	.161	15.359	9	.087	.716	1.000	.250

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	1328.844	4	332.211	1.410	.248
	Greenhouse-Geisser	1328.844	2.865	463.822	1.410	.260
	Huynh-Feldt	1328.844	4.000	332.211	1.410	.248
	Lower-bound	1328.844	1.000	1328.844	1.410	.262
Error(condition)	Sphericity Assumed	9422.416	40	235.560		
	Greenhouse-Geisser	9422.416	28.650	328.881		
	Huynh-Feldt	9422.416	40.000	235.560		
	Lower-bound	9422.416	10.000	942.242		

Unadjusted Pairwise Comparisons

Pairwise Comparisons

Measure: MEASURE_1

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	5.924	5.853	.335	-7.117	18.966
	3	14.272	7.158	.074	-1.677	30.222
	4	9.927	4.788	.065	-.742	20.596
	5	11.123	7.261	.157	-5.055	27.300
2	1	-5.924	5.853	.335	-18.966	7.117
	3	8.348	7.519	.293	-8.406	25.102
	4	4.003	7.188	.590	-12.013	20.018
	5	5.199	7.616	.510	-11.772	22.169
3	1	-14.272	7.158	.074	-30.222	1.677
	2	-8.348	7.519	.293	-25.102	8.406
	4	-4.345	7.019	.550	-19.984	11.294
	5	-3.149	5.985	.610	-16.485	10.186
4	1	-9.927	4.788	.065	-20.596	.742
	2	-4.003	7.188	.590	-20.018	12.013
	3	4.345	7.019	.550	-11.294	19.984
	5	1.196	3.982	.770	-7.676	10.067
5	1	-11.123	7.261	.157	-27.300	5.055
	2	-5.199	7.616	.510	-22.169	11.772
	3	3.149	5.985	.610	-10.186	16.485
	4	-1.196	3.982	.770	-10.067	7.676

Based on estimated marginal means

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

Bonferroni-Adjusted Pairwise Comparisons

Pairwise Comparisons

Measure: MEASURE_1

(I) condition	(J) condition	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	5.924	5.853	1.000	-15.038	26.887
	3	14.272	7.158	.742	-11.365	39.909
	4	9.927	4.788	.649	-7.222	27.076
	5	11.123	7.261	1.000	-14.880	37.126
2	1	-5.924	5.853	1.000	-26.887	15.038
	3	8.348	7.519	1.000	-18.582	35.277
	4	4.003	7.188	1.000	-21.740	29.745
	5	5.199	7.616	1.000	-22.079	32.476
3	1	-14.272	7.158	.742	-39.909	11.365
	2	-8.348	7.519	1.000	-35.277	18.582
	4	-4.345	7.019	1.000	-29.482	20.792
	5	-3.149	5.985	1.000	-24.584	18.285
4	1	-9.927	4.788	.649	-27.076	7.222
	2	-4.003	7.188	1.000	-29.745	21.740
	3	4.345	7.019	1.000	-20.792	29.482
	5	1.196	3.982	1.000	-13.064	15.456
5	1	-11.123	7.261	1.000	-37.126	14.880
	2	-5.199	7.616	1.000	-32.476	22.079
	3	3.149	5.985	1.000	-18.285	24.584
	4	-1.196	3.982	1.000	-15.456	13.064

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

6. Power

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	.131	8.991	9	.470	.534	.837	.250

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	150786.906	4	37696.726	12.309	.000
	Greenhouse-Geisser	150786.906	2.134	70645.149	12.309	.001
	Huynh-Feldt	150786.906	3.348	45041.213	12.309	.000
	Lower-bound	150786.906	1.000	150786.906	12.309	.013
Error(condition)	Sphericity Assumed	73499.074	24	3062.461		
	Greenhouse-Geisser	73499.074	12.807	5739.173		
	Huynh-Feldt	73499.074	20.087	3659.123		
	Lower-bound	73499.074	6.000	12249.846		

Unadjusted Pairwise Comparisons

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	-86.283*	16.357	.002	-126.307	-46.260
	3	-151.221*	30.069	.002	-224.797	-77.645
	4	-148.963*	29.491	.002	-221.124	-76.803
	5	-185.903*	37.899	.003	-278.640	-93.167
2	1	86.283*	16.357	.002	46.260	126.307
	3	-64.937	34.034	.105	-148.216	18.341
	4	-62.680	32.091	.099	-141.205	15.845
	5	-99.620*	37.418	.037	-191.177	-8.062
3	1	151.221*	30.069	.002	77.645	224.797
	2	64.937	34.034	.105	-18.341	148.216
	4	2.258	25.547	.932	-60.254	64.769
	5	-34.682	18.054	.103	-78.859	9.495
4	1	148.963*	29.491	.002	76.803	221.124
	2	62.680	32.091	.099	-15.845	141.205
	3	-2.258	25.547	.932	-64.769	60.254
	5	-36.940	26.557	.214	-101.923	28.044
5	1	185.903*	37.899	.003	93.167	278.640
	2	99.620*	37.418	.037	8.062	191.177
	3	34.682	18.054	.103	-9.495	78.859
	4	36.940	26.557	.214	-28.044	101.923

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).

Bonferroni-Adjusted Pairwise Comparisons

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	-86.283*	16.357	.019	-156.892	-15.675
	3	-151.221*	30.069	.024	-281.023	-21.419
	4	-148.963*	29.491	.023	-276.269	-21.658
	5	-185.903*	37.899	.027	-349.508	-22.298
2	1	86.283*	16.357	.019	15.675	156.892
	3	-64.937	34.034	1.000	-211.857	81.983
	4	-62.680	32.091	.986	-201.213	75.853
	5	-99.620	37.418	.374	-261.145	61.906
3	1	151.221*	30.069	.024	21.419	281.023
	2	64.937	34.034	1.000	-81.983	211.857
	4	2.258	25.547	1.000	-108.025	112.540
	5	-34.682	18.054	1.000	-112.618	43.254
4	1	148.963*	29.491	.023	21.658	276.269
	2	62.680	32.091	.986	-75.853	201.213
	3	-2.258	25.547	1.000	-112.540	108.025
	5	-36.940	26.557	1.000	-151.583	77.704
5	1	185.903*	37.899	.027	22.298	349.508
	2	99.620	37.418	.374	-61.906	261.145
	3	34.682	18.054	1.000	-43.254	112.618
	4	36.940	26.557	1.000	-77.704	151.583

Based on estimated marginal means

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

b. Adjustment for multiple comparisons: Bonferroni.

7. Impulse

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	.000	40.094	9	.000	.282	.303	.250

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.

Test Statistics[a]

N	7
Chi-Square	18.057
df	4
Asymp. Sig.	.001

a. Friedman Test

Test Statistics[a]

	avg_impulse_140 - avg_impulse_120	avg_impulse_150 - avg_impulse_120	avg_impulse_160 - avg_impulse_120	avg_impulse_170 - avg_impulse_120	avg_impulse_150 - avg_impulse_140	avg_impulse_160 - avg_impulse_140	avg_impulse_170 - avg_impulse_140	avg_impulse_160 - avg_impulse_150	avg_impulse_170 - avg_impulse_150	avg_impulse_170 - avg_impulse_160
Z	-2.197[b]	-2.366[b]	-2.366[b]	-2.366[b]	-1.521[b]	-1.183[b]	-2.028[b]	-.338[b]	-1.859[b]	-1.690[b]
Asymp. Sig. (2-tailed)	.028	.018	.018	.018	.128	.237	.043	.735	.063	.091

a. Wilcoxon Signed Ranks Test

b. Based on positive ranks.

8. Average Angular Velocity

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	.277	15.945	9	.070	.631	.782	.250

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	64512.454	4	16128.113	42.026	.000
	Greenhouse-Geisser	64512.454	2.525	25551.596	42.026	.000
	Huynh-Feldt	64512.454	3.126	20637.168	42.026	.000
	Lower-bound	64512.454	1.000	64512.454	42.026	.000
Error(condition)	Sphericity Assumed	21490.675	56	383.762		
	Greenhouse-Geisser	21490.675	35.347	607.990		
	Huynh-Feldt	21490.675	43.764	491.053		
	Lower-bound	21490.675	14.000	1535.048		

Unadjusted Pairwise Comparisons

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	-40.095*	5.393	.000	-51.661	-28.529
	3	-62.993*	5.996	.000	-75.852	-50.133
	4	-64.546*	5.844	.000	-77.080	-52.013
	5	-86.408*	8.464	.000	-104.562	-68.255
2	1	40.095*	5.393	.000	28.529	51.661
	3	-22.898*	7.682	.010	-39.375	-6.421
	4	-24.452*	8.628	.013	-42.958	-5.946
	5	-46.314*	9.656	.000	-67.024	-25.604
3	1	62.993*	5.996	.000	50.133	75.852
	2	22.898*	7.682	.010	6.421	39.375
	4	-1.554	6.357	.810	-15.187	12.080
	5	-23.416*	6.020	.002	-36.328	-10.504
4	1	64.546*	5.844	.000	52.013	77.080
	2	24.452*	8.628	.013	5.946	42.958
	3	1.554	6.357	.810	-12.080	15.187
	5	-21.862*	6.125	.003	-34.999	-8.725
5	1	86.408*	8.464	.000	68.255	104.562
	2	46.314*	9.656	.000	25.604	67.024
	3	23.416*	6.020	.002	10.504	36.328
	4	21.862*	6.125	.003	8.725	34.999

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).

Bonferroni-Adjusted Pairwise Comparisons

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	-40.095*	5.393	.000	-58.029	-22.160
	3	-62.993*	5.996	.000	-82.933	-43.053
	4	-64.546*	5.844	.000	-83.981	-45.112
	5	-86.408*	8.464	.000	-114.557	-58.260
2	1	40.095*	5.393	.000	22.160	58.029
	3	-22.898	7.682	.099	-48.447	2.651
	4	-24.452	8.628	.133	-53.147	4.243
	5	-46.314*	9.656	.003	-78.426	-14.201
3	1	62.993*	5.996	.000	43.053	82.933
	2	22.898	7.682	.099	-2.651	48.447
	4	-1.554	6.357	1.000	-22.694	19.586
	5	-23.416*	6.020	.016	-43.438	-3.394
4	1	64.546*	5.844	.000	45.112	83.981
	2	24.452	8.628	.133	-4.243	53.147
	3	1.554	6.357	1.000	-19.586	22.694
	5	-21.862*	6.125	.031	-42.232	-1.492
5	1	86.408*	8.464	.000	58.260	114.557
	2	46.314*	9.656	.003	14.201	78.426
	3	23.416*	6.020	.016	3.394	43.438
	4	21.862*	6.125	.031	1.492	42.232

Based on estimated marginal means

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

b. Adjustment for multiple comparisons: Bonferroni.

9. Angle at Peak Torque

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	.221	18.722	9	.029	.543	.647	.250

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.

Test Statistics[a]

N	15
Chi-Square	5.173
df	4
Asymp. Sig.	.270

a. Friedman Test

Test Statistics[a]

	ang@PT_140 - ang@PT_120	ang@PT_150 - ang@PT_120	ang@PT_160 - ang@PT_120	ang@PT_170 - ang@PT_120	ang@PT_150 - ang@PT_140	ang@PT_160 - ang@PT_140	ang@PT_170 - ang@PT_140	ang@PT_160 - ang@PT_150	ang@PT_170 - ang@PT_150	ang@PT_170 - ang@PT_160
Z	-.852[b]	-.166[b]	-1.254[c]	-.876[b]	-.682[b]	-1.704[c]	-.414[b]	-1.823[c]	-.166[c]	-1.065[b]
Asymp. Sig. (2-tailed)	.394	.868	.210	.381	.496	.088	.679	.068	.868	.287

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. Based on positive ranks.

10. Torque at 90^o

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	.493	8.792	9	.461	.715	.918	.250

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	1106.303	4	276.576	1.689	.165
	Greenhouse-Geisser	1106.303	2.859	386.917	1.689	.187
	Huynh-Feldt	1106.303	3.670	301.425	1.689	.171
	Lower-bound	1106.303	1.000	1106.303	1.689	.215
Error(condition)	Sphericity Assumed	9168.037	56	163.715		
	Greenhouse-Geisser	9168.037	40.030	229.030		
	Huynh-Feldt	9168.037	51.383	178.424		
	Lower-bound	9168.037	14.000	654.860		

11. Peak Torque as a Percentage of Calculated Maximal Isometric Torque

Mauchly's Test of Sphericity[a]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b] Greenhouse-Geisser	Epsilon[b] Huynh-Feldt	Epsilon[b] Lower-bound
condition	.571	6.965	9	.644	.771	1.000	.250

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	6133.430	4	1533.357	12.599	.000
	Greenhouse-Geisser	6133.430	3.086	1987.817	12.599	.000
	Huynh-Feldt	6133.430	4.000	1533.357	12.599	.000
	Lower-bound	6133.430	1.000	6133.430	12.599	.003
Error(condition)	Sphericity Assumed	6815.672	56	121.708		
	Greenhouse-Geisser	6815.672	43.197	157.781		
	Huynh-Feldt	6815.672	56.000	121.708		
	Lower-bound	6815.672	14.000	486.834		

Unadjusted Pairwise Comparisons

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	7.540*	3.454	.047	.132	14.949
	3	16.867*	3.340	.000	9.704	24.031
	4	17.817*	3.839	.000	9.584	26.049
	5	26.201*	4.846	.000	15.808	36.595
2	1	-7.540*	3.454	.047	-14.949	-.132
	3	9.327*	3.805	.028	1.167	17.487
	4	10.276*	3.608	.013	2.538	18.015
	5	18.661*	5.237	.003	7.429	29.894
3	1	-16.867*	3.340	.000	-24.031	-9.704
	2	-9.327*	3.805	.028	-17.487	-1.167
	4	.949	3.869	.810	-7.349	9.247
	5	9.334*	3.772	.027	1.245	17.423
4	1	-17.817*	3.839	.000	-26.049	-9.584
	2	-10.276*	3.608	.013	-18.015	-2.538
	3	-.949	3.869	.810	-9.247	7.349
	5	8.385	4.106	.060	-.422	17.191
5	1	-26.201*	4.846	.000	-36.595	-15.808
	2	-18.661*	5.237	.003	-29.894	-7.429
	3	-9.334*	3.772	.027	-17.423	-1.245
	4	-8.385	4.106	.060	-17.191	.422

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).

Bonferroni-Adjusted Pairwise Comparisons

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	7.540	3.454	.466	-3.948	19.028
	3	16.867*	3.340	.002	5.759	27.975
	4	17.817*	3.839	.004	5.051	30.582
	5	26.201*	4.846	.001	10.086	42.317
2	1	-7.540	3.454	.466	-19.028	3.948
	3	9.327	3.805	.280	-3.326	21.980
	4	10.276	3.608	.129	-1.723	22.276
	5	18.661*	5.237	.031	1.244	36.079
3	1	-16.867*	3.340	.002	-27.975	-5.759
	2	-9.327	3.805	.280	-21.980	3.326
	4	.949	3.869	1.000	-11.917	13.816
	5	9.334	3.772	.267	-3.209	21.877
4	1	-17.817*	3.839	.004	-30.582	-5.051
	2	-10.276	3.608	.129	-22.276	1.723
	3	-.949	3.869	1.000	-13.816	11.917
	5	8.385	4.106	.604	-5.270	22.040
5	1	-26.201*	4.846	.001	-42.317	-10.086
	2	-18.661*	5.237	.031	-36.079	-1.244
	3	-9.334	3.772	.267	-21.877	3.209
	4	-8.385	4.106	.604	-22.040	5.270

Based on estimated marginal means

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

b. Adjustment for multiple comparisons: Bonferroni.

12. Torque at 90° as a Percentage of Calculated Maximal Isometric Torque

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	.540	7.662	9	.572	.761	.996	.250

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	6256.964	4	1564.241	12.527	.000
	Greenhouse-Geisser	6256.964	3.042	2056.536	12.527	.000
	Huynh-Feldt	6256.964	3.982	1571.157	12.527	.000
	Lower-bound	6256.964	1.000	6256.964	12.527	.003
Error(condition)	Sphericity Assumed	6992.580	56	124.867		
	Greenhouse-Geisser	6992.580	42.595	164.166		
	Huynh-Feldt	6992.580	55.753	125.420		
	Lower-bound	6992.580	14.000	499.470		

Unadjusted Pairwise Comparisons

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	8.316*	3.834	.048	.093	16.539
	3	17.445*	3.198	.000	10.587	24.304
	4	16.181*	3.810	.001	8.009	24.353
	5	27.129*	4.788	.000	16.861	37.397
2	1	-8.316*	3.834	.048	-16.539	-.093
	3	9.129	4.267	.051	-.023	18.281
	4	7.865*	3.614	.047	.113	15.616
	5	18.813*	5.377	.004	7.280	30.346
3	1	-17.445*	3.198	.000	-24.304	-10.587
	2	-9.129	4.267	.051	-18.281	.023
	4	-1.264	3.313	.708	-8.371	5.842
	5	9.684*	3.603	.018	1.956	17.412
4	1	-16.181*	3.810	.001	-24.353	-8.009
	2	-7.865*	3.614	.047	-15.616	-.113
	3	1.264	3.313	.708	-5.842	8.371
	5	10.948*	4.470	.028	1.361	20.536
5	1	-27.129*	4.788	.000	-37.397	-16.861
	2	-18.813*	5.377	.004	-30.346	-7.280
	3	-9.684*	3.603	.018	-17.412	-1.956
	4	-10.948*	4.470	.028	-20.536	-1.361

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).

Bonferroni-Adjusted Pairwise Comparisons

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	8.316	3.834	.478	-4.434	21.067
	3	17.445*	3.198	.001	6.811	28.080
	4	16.181*	3.810	.008	3.510	28.852
	5	27.129*	4.788	.001	11.207	43.051
2	1	-8.316	3.834	.478	-21.067	4.434
	3	9.129	4.267	.505	-5.063	23.320
	4	7.865	3.614	.472	-4.156	19.885
	5	18.813*	5.377	.035	.930	36.696
3	1	-17.445*	3.198	.001	-28.080	-6.811
	2	-9.129	4.267	.505	-23.320	5.063
	4	-1.264	3.313	1.000	-12.283	9.755
	5	9.684	3.603	.177	-2.299	21.666
4	1	-16.181*	3.810	.008	-28.852	-3.510
	2	-7.865	3.614	.472	-19.885	4.156
	3	1.264	3.313	1.000	-9.755	12.283
	5	10.948	4.470	.281	-3.918	25.814
5	1	-27.129*	4.788	.001	-43.051	-11.207
	2	-18.813*	5.377	.035	-36.696	-.930
	3	-9.684	3.603	.177	-21.666	2.299
	4	-10.948	4.470	.281	-25.814	3.918

Based on estimated marginal means

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

b. Adjustment for multiple comparisons: Bonferroni.