

ASSESSING INTER-DAY RELIABILITY OF SURFACE EMG AMPLITUDE FOR RESISTANCE
TRAINING EXERCISE SELECTION

Michael W. L. Croskery

A thesis submitted in partial fulfillment of the requirements for the
M.Sc. degree in Human Kinetics

School of Human Kinetics
Faculty of Health Sciences
University of Ottawa

Table of Contents

Dedication..... v

Acknowledgements..... vi

List of Abbreviations..... vii

List of Figures..... viii

List of Tables..... ix

ABSTRACT..... x

CHAPTER 1: INTRODUCTION 1

CHAPTER 2: REVIEW OF LITERATURE..... 5

 2.1 Neural response and adaptations to resistance training..... 5

 2.1.1 Motor Unit Recruitment..... 6

 2.1.2 Motor Unit Firing Frequency and Synchronization 7

 2.1.3 Cortical and Subcortical Changes 10

 2.1.4 Summary of Neural Adaptations from Resistance Training..... 10

 2.2 Use of Bipolar SEMG in Exercise Selection 11

 2.3 Classification of Intra-class Correlation 13

 2.4 Inter-day Reliability of Surface Electromyography in Dynamic Movements 14

 2.5 Other Factors Affecting Inter-Day Reliability of SEMG Amplitude 16

 2.6 Inertial-based Motion Capture 18

 2.7 Summary 18

CHAPTER 3: METHODS 20

 3.1 Participants..... 20

3.2 Consent	21
3.3 Study Design.....	21
3.4 Location of Collection	21
3.5 Session One: Exercise Familiarization and Strength	22
3.6 Sessions Two through Five	25
3.7 Data Analysis	28
3.7.1 Kinematics	28
3.7.2 Event Detection.....	29
3.7.3 SEMG Analysis.....	31
3.8 Statistical Analysis	31
CHAPTER 4: RESULTS	34
4.1 Descriptive Data.....	34
4.2 Effect of Exercise and Trial on Angular Velocity	36
4.3 Effect of Exercise and Trial on SEMG Amplitude.....	37
4.4 Reliability and Repeatability of SEMG over Trials	39
CHAPTER 5: DISCUSSION.....	42
CHAPTER 6: CONCLUSION.....	49
CHAPTER 7: REFERENCES	50
Appendix A.....	78
Appendix B.....	80
Appendix C.....	85

Appendix D.....	87
Appendix E.....	88

Dedication

I would like to dedicate this thesis to my past and current clients who, over the past 30 years, have trusted me to collaborate with them toward reaching their goals. Each of you has taught me something unique that I carry with me and has made me realize that the individual truly defines and determines the best way forward. I am grateful to the well over a thousand individuals who allowed me to witness and contribute to what it takes to set records, reach new physical personal bests, improve health and wellness, increase longevity and mental stamina, and gracefully prepare for the inevitable late stages of life. I hope this thesis provides valuable information to those practicing in a similar field to help their patients and clients reach their personal goals.

Acknowledgements

“Why are you doing that?” would often be the first question many asked as to why I was returning to school after nearly three decades as an exercise physiologist and strength and conditioning coach. This recurring question was valid; my response was, “how to find answers to difficult questions.” I would like to recognize and thank many talented, intelligent, and thoughtful individuals who contributed to this thesis and made this journey a unique and rewarding experience.

First, I would like to express my deepest gratitude to Dr. Ryan Graham, who accepted me as his student and provided invaluable guidance and support over the past two years. His knowledge, experience, and leadership garner my utmost respect, and I am thankful to have had the opportunity to learn from such a great scientist. I also want to thank my committee members, Dr. Tony Carlsen and Dr. Janie Cournoyer, for their time, feedback, and direction in helping me shape this thesis into what I believe applies to the decisions clinicians can use in their practice.

Second, I would like to thank my lab mates for their warm welcome, generosity with their time, and expertise in helping me navigate this journey. Victor, thank you for your meticulous proofreading and insightful feedback and for sharing your knowledge and time throughout this process. Thank you, Alex, for your invaluable assistance in reviewing the ethics submission. Being part of such a dynamic and talented group has been a privilege.

Lastly, but by no means least, I would like to thank my family. To my beautiful and inspiring wife, Tally, who has supported and cheered me on with great enthusiasm for over 25 years, especially since I started this process in the fall of 2022. I am eternally grateful and proud to have you by my side every step of the way. To my wonderful and talented daughter, Saila, who inspired me with her resilience and allowed me to share the experience with her while not “cramping her style.” I love and appreciate you both; thank you for being so great!

List of Abbreviations

AIC	Akaike Information Criteria
ARV	Average Rectified Value
BB	Biceps Brachii
BPM	Beats Per Minute
CONC	Concentration Curl
CV	Coefficient of Variation
DBELL	Dumbbell Curl
DHARMa	Diagnostics for Hierarchal Regression Models
DYNnorm	Normalized Surface EMG to the Peak of a Dynamic Contraction
EMG	Electromyography
GCS	Global Coordinate System
GLMM	Generalized Linear Mixed Model
HAMM	Hammer Curl
Hz	Hertz
ICC	Intraclass Coefficient Correlation
INCL	Incline Curl
IMU	Inertial Measurement Unit
LCS	Local Coordinate System
LMM	Linear mixed model
MDC	Minimum Detectable Change
MU	Motor Units
MUAP	Motor Unit Action Potential
MVC	Maximal Voluntary Contraction
MVIC	Maximal Voluntary Isometric Contraction
MVICnorm	Normalized Surface EMG to a Maximal Voluntary Isometric Contraction
RMS	Root Mean Square
SB	Spearman-Brown Reliability Coefficient
SD	Standard Deviation
SEM	Standard Error of Measurement
SEMG	Surface Electromyography
TE	Typical Error
TEM	Typical Error of Measurement

List of Figures

Figure 1. Resistance training arm curl exercises.....	23
Figure 2. Apparatus to measure MVIC elbow flexor force production.	24
Figure 3. Anterior, lateral, and posterior views of SEMG and IMU sensor placement.	26
Figure 4. Concentric and eccentric start and stop events.	29
Figure 5. Raincloud plots of each exercise and the respective trial for MVCnorm.	34
Figure 6. Raincloud plots of each exercise and the respective trial for DYNnorm.	34
Figure 7. Individual data for each exercise normalized to an MVC.	37
Figure 8. Individual data for each exercise normalized to the dynamic peak.	37

List of Tables

Table 1. Summary of Neural Adaptations from Resistance Training.....	11
Table 2. Participant Demographics	20
Table 3. Timing of data collection sessions	21
Table 4. Prescribed load calculations from MVIC force.....	25
Table 5. Total number of events that were removed.	30
Table 6. Participant descriptive data for soreness and fatigue	35
Table 7. Descriptive data of exercises for MVCnorm and DYNnorm.....	35
Table 8. Individual consistency ICC _{2,k} values	36
Table 9. Relational effect size contrasts for MVCnorm.....	38
Table 10. Relational effect size contrasts for DYNnorm	39
Table 11. Reliability and repeatability	40

ABSTRACT

In resistance training, surface electromyography (SEMG) assesses muscle excitation and aids in exercise selection for strength, hypertrophy, and performance. However, SEMG amplitude variability may limit its predictive power for training adaptation. This study evaluated the reliability and exercise relationship of SEMG amplitudes of the biceps brachii (BB) during the concentration (CONC), dumbbell (DBELL), hammer (HAMM), and incline (INCL) resistance arm curl exercises over four separate sessions.

Eight trained (5 males and 3 females) and 7 untrained (4 males and 3 females) participants (37 ± 15 years) performed 7 repetitions per exercise to a metronome set to 30 BPM (2 s each for concentric and eccentric movements followed by a 2 s pause) at an intensity of one-third of the elbow flexion maximum voluntary isometric contraction (MVIC) force. The exercise sequence was randomly selected, and rest periods between exercises lasted $4 (\pm 1)$ min. SEMG signals were processed using the root mean square method with a 200 ms window. The mean SEMG amplitude of the last 4 repetitions was normalized to the peak value from an MVIC of the BB (MVCnorm) and to the peak value of the BB obtained during the last four repetitions of the DBELL (DYNnorm). A generalized linear mixed model was performed to examine the differences in normalized amplitude for the exercises, sessions, and the interaction between exercises and sessions. Intraclass correlation coefficients (ICC) were calculated to determine variability across the four sessions for the model and the individual exercises. Pearson correlations of contrast effect sizes between exercises were performed to assess if the magnitude of the effect sizes changed over multiple trials.

The main effect of exercise was significant for both MVCnorm ($p = .039$) and DYNnorm ($p = .049$). There were no significant main effects of sessions or exercise:trial interaction for both normalization methods. Post hoc tests indicated CONC MVCnorm and DYNnorm were significantly higher than HAMM MVCnorm ($p = .023$, ES = 0.694 or large) and DYNnorm ($p = .031$, ES = 0.909 or large), respectively. Participant repeatability was higher in MVCnorm ($R = 0.543$) than in DYNnorm ($R =$

0.217). Overall, model-adjusted ICC values suggest moderate reliability for both normalization methods; however, individual exercises for MVCnorm ranged from moderate to good agreement, and DYNnorm showed poor to moderate agreement. In both normalization methods, CONC showed the highest reliability. In contrast, HAMM showed the lowest reliability, suggesting that the degree of contribution of the brachialis and brachioradialis in the HAMM may have affected reliability. Pearson correlations between the magnitude of the effect size across trials were strong to very strong regardless of the normalization method, indicating that the relationship between SEMG amplitude magnitudes between exercises remained throughout the trials.

Clinicians and researchers should be aware that although SEMG amplitude shows high heterogeneity between individuals, reliability for resistance training exercise generally demonstrates favourable results with the rank relationship between exercises maintained across trials. Exercises involving multiple synergist muscles that significantly contribute to the motion may cause reliability to fluctuate and affect target muscle excitation. This variability should be considered during training program design and to investigate the influence of SEMG amplitude on training adaptation.

CHAPTER 1: INTRODUCTION

Sports scientists use surface electromyography (SEMG) to assess muscle excitation and relate this signal to activation of individual or multiple muscles concerning movements related to performance, rehabilitation, or injury prevention. These signals can then be further processed to investigate muscle activation timing, fatigue, and the synergy of multiple muscle groups to interpret a specific muscle's role in force production (Taborri et al., 2020). Although muscle excitation and activation are often used interchangeably, excitation refers more specifically to the depolarization of the motor unit that results in a cascade of events that leads to calcium release within the muscle fibre (Farina et al., 2016). This calcium release causes myosin to bind to actin, activating the muscle and creating muscle force (Enoka & Duchateau, 2016). Muscle excitation results from the neural signal sent to the muscle fibre and motor units. In contrast, muscle activation is the mechanical coupling of the actin-myosin cross bridge that subsequently occurs. An individual can not have muscle activation without muscle excitation.

Measuring muscle excitation during resistance training exercises and consequently inferring a certain degree of muscle activation is one application of SEMG used in exercise research and clinical applications (Delgado et al., 2019; Solstad et al., 2020; Uysal et al., 2022). Comparing muscle excitation between exercises aims to determine which exercise may best match the client's goals based on the degree of SEMG amplitude and, consequently, estimated muscle activation. For example, a muscle with a high muscle excitation compared to the same muscle under the same recording conditions with a low excitation would suggest greater motor unit recruitment and higher muscle tension. This higher excitation level may indicate a more significant stimulus for increased whole-muscle hypertrophy and strength to the targeted muscle over the low excitation condition. SEMG amplitude during exercise is then hierarchically classified based on estimating the intensity of contraction, and predictions are made as to which appropriate exercises should strengthen the target muscles to improve performance (Daly et al., 2019; Jakobsen et al., 2019). The findings are then used to support the choice of an exercise that may result in

greater strength and or hypertrophy of the affected muscle during resistance training routines (Alkner & Bring, 2019; Saeterbakken et al., 2019; Snarr et al., 2017).

As SEMG equipment becomes more available due to decreased cost and improved distribution, this application has been gaining popularity among strength and conditioning professionals, rehabilitation therapists, and even fitness media influencers on platforms like YouTube (Ethier, 2022; Humiston, 2022). This approach for exercise selection seems intuitive, considering SEMG is generally reflective of greater muscle tension particularly during isometric contractions (Kamen, 2010; Uliam et al., 2012; Winter, 2009) and after appropriate signal processing (Potvin & Brown, 2004), and that a certain amount of muscle tension is necessary to generate increases in muscle hypertrophy (Lasevicius et al., 2018; Schoenfeld et al., 2021) and strength (Haff & Triplett, 2016; Lopez et al., 2021).

However, using SEMG amplitude to approximate the potential long-term adaptations is not without controversy (Vigotsky et al., 2022). A curvilinear relationship has been observed between SEMG amplitude and force production for the biceps brachii (Sbriccoli et al., 2003), vastus medialis and rectus femoris (Alkner et al., 2000) as well as the upper trapezius (Jensen & Westgaard, 1995). However, muscle activation and its relation to neuromuscular excitation appear to be more linear in other muscles (Alkner et al., 2000; Christie et al., 2016; Praagman et al., 2003) and may also vary at different intensities (Jensen et al., 2012), signal processing techniques (Potvin & Brown, 2004), and training status (Amarantini & Bru, 2015). These factors can make it challenging to interpret what a greater or lesser SEMG amplitude truly represents as increased strength and muscle hypertrophy from resistance training is also a result of a combination of neural recruitment strategies (Aagaard et al., 2020; Gardiner, 2011), intracellular signalling (Lim et al., 2022), myokine production (Zunner et al., 2022), genetics (Roberts et al., 2018), and exogenous variables such as nutritional status and exercise program design (Joanisse et al., 2020; Schoenfeld, 2016).

Indirect evidence suggests that this relationship to longitudinal outcome could exist and that SEMG amplitude may indicate future exercise outcomes. Several studies investigating muscle excitation

in resistance exercise for the muscle of the upper thigh have shown that proportionally greater hypertrophy and strength gains do occur in combination with greater SEMG amplitude in the rectus femoris and the vastus muscle groups of the upper thigh during knee extension and the squat respectively (Ema et al., 2013; Spiliopoulou et al., 2022; Zabaleta-Korta et al., 2021). In addition, SEMG biofeedback during post-knee surgery therapy results in more significant strength gains than those who did not use this method (Karaborklu Argut et al., 2022). Contrary to these studies, others have found similar hypertrophy between slow and fast repetition speed along with respectively mean lower and higher SEMG amplitudes (Lacerda et al., 2021) as well as in studies investigating the effect of low and high loads with presumably initial lower and higher muscle excitation (Jenkins et al., 2015; Schoenfeld et al., 2021; Schoenfeld et al., 2017). Mental imagery exercises associated with and without muscle activation, as estimated with SEMG, have also shown increased force production in untrained participants (Yue & Cole, 1992).

Even though inferring longitudinal increases in strength and muscle hypertrophy from acute SEMG amplitude should be done cautiously (Vigotsky et al., 2022), the assumption is that SEMG amplitudes are reliable over multiple days when measured during dynamic resistance training exercise. During dynamic contractions, inter-individual differences in amplitude can be affected by several factors under similar load conditions. These conditions include tissue thickness and fluid between the electrodes and the target muscle, which affects the distance of the active motor units (MU) from the electrodes, the location of the electrodes, and architectural changes within the muscle (Farina et al., 2004; Guilhem et al., 2011; Vieira et al., 2017). In addition, individual differences in neuromuscular activation and recruitment strategies while performing the same exercise can result in differences in EMG amplitude across the same involved muscles (Boyer et al., 2021; Crouzier et al., 2019).

Amplitude cancellation of the SEMG signal due to the overlap of motor unit action potentials can also affect the ability to interpret muscle excitation reliably during intensities higher than 60% of a maximal dynamic voluntary contraction (MVC) under specific signal processing techniques (Dideriksen & Farina, 2019; Kamen, 2010), thus affecting the relationship to force production (Keenan et al., 2005).

As most resistance training occurs above this intensity threshold, as well as the wide variability seen in SEMG amplitudes over inter-day periods for various movements (Brandt et al., 2017), ranking exercise effectiveness based on repeatable results would be essential to determine if electromyography is suitable as a longitudinal proxy for performance increases. Therefore, determining whether SEMG amplitudes are repeatable and reliable across several days would be vital to determine whether using SEMG amplitudes for choosing resistance training exercises is appropriate.

Regarding exercise selection protocols to determine which exercise results in the highest SEMG amplitude, there is a lack in the current literature of direct studies examining initial acute SEMG amplitudes and the inter-day reliability of the relationship between exercises over several sessions. Investigating this approach would provide valuable information to professionals in both clinical and applied settings in designing optimal training routines to enhance strength and muscle hypertrophy. In addition, the vast number of published studies over the past decades that have used this inference process to select exercises would have increased value in their recommendations to incorporate these exercises into structured rehabilitative, fitness, and performance-oriented routines if SEMG amplitudes during resistance training exercises are determined to be reliable across multiple days. Therefore, the objective of this thesis is to evaluate the biceps brachii during four unilateral arm resistance training exercises (supinated grip dumbbell curl, neutral grip hammer curl, supinated grip incline curl, and supinated grip concentration curl) across two different normalization methods to determine if the magnitudes of the relative SEMG amplitudes between exercises are maintained over multiple sessions separated by several days.

CHAPTER 2: REVIEW OF LITERATURE

2.1 Neural response and adaptations to resistance training

The main benefit of resistance training is that it increases muscle strength and hypertrophy. These benefits are achieved through adaptations in how the nervous system activates the involved muscles (interpreted as neural drive as measured by SEMG amplitude) to increase tension and thus trigger the necessary adaptations in the morphological qualities of the skeletal muscle tissue involved in the movements. After many resistance training sessions that take place over several weeks to months, morphological adaptations include increases in muscle fascicle length (Santaniello et al., 2020) and pennation angle (Ema et al., 2013; Kawakami et al., 1995), increases in the cross-sectional area of the involved muscle fibres and consequently associated muscles (Lasevicius et al., 2018; Schoenfeld et al., 2017), and increases in tendon stiffness (Wiesinger et al., 2015). These changes in the muscle tissue play a significant role in the resultant force production capabilities. However, it is the neural signals generated in the cortex, sub-subcortex, spinal pathways of the central nervous system, as well as the motor neurons located within the muscle that control whether the muscle tissues activate or not to create this force production (Santos et al., 2023). Neural adaptations to resistance training may include increases in firing frequency, motor unit synchronization, decreased recruitment thresholds of larger motor units, cortical and subcortical changes, as well as improvements in the efficiency of muscle coordination of the involved agonist, antagonist, and synergistic muscles (Carroll et al., 2001). Although these are universal adaptations that occur due to resistance training, there appears to be significant heterogeneity among individuals, and these adaptations that contribute to performance need to be clarified (Elgueta-Cancino et al., 2022).

Neural adaptations occur across all age groups, including youth and older adults (Bemben & Murphy, 2001; Herda et al., 2024; Walker, 2021) and are similar in both sexes (Giuriato et al., 2024; Häkkinen et al., 1992; Multer, 2002) although females may have more significant decreases in SEMG activation levels during detraining periods (Deschenes et al., 2009). As many existing studies utilized

male participants, it is essential to note that there remains a paucity of research concerning sex differences in neuromuscular adaptations from resistance training. However, it is believed that these adaptations should be similar (Haff & Triplett, 2016). These neural adaptations occur most notably in untrained participants during the initial stages of a strength training routine, with hypertrophy playing a more significant role after two to four weeks of training (Carroll et al., 2001; Folland & Williams, 2007). Although these adaptations appear to return to normal after three months of detraining, SEMG of the quadriceps muscle and maximal strength during eccentric contractions is preserved, suggesting that retention of these adaptations may also be specific to the muscle and the contraction type (Andersen et al., 2005). Therefore, changes in activity levels incorporating strength training should be considered as potential influential factors in examining changes in normalized SEMG amplitude within two weeks and possibly up to 3 months, depending on the scope of the study.

2.1.1 Motor Unit Recruitment

Increases in muscular force depend on the recruited motor unit pool of innervated muscle fibres. This recruited motor unit pool generally recruits in an orderly manner from the smallest motor unit size toward larger motor units in a hierarchical manner described as the 'size principle' (Henneman et al., 1965). However, exceptions appear during special situations, such as ballistic and fatiguing contractions and certain environmental conditions (Hodson-Tole & Wakeling, 2009). Increases in force production is a result of involving more and increasingly larger motor units (Riek & Bawa, 1992; Sale, 1988) with upper limits in maximal recruitment seen at approximately 80% to 90% in the arm flexors (Kukulka & Clamann, 1981), deltoid (De Luca et al., 1982), and tibialis anterior (Cutsem et al., 1997) but lower intensities in the hand muscles (Jesunathadas et al., 2010). In most cases, higher SEMG amplitudes associated with higher muscular tension are mainly due to the summation of the recruited motor unit pool (De Luca, 1997; Kamen, 2010; Winter, 2009).

The level of excitability (or recruitment threshold) depends on the size of the motor unit, with larger motor units requiring a higher level of neural excitability and thus having higher recruitment

thresholds (Gardiner, 2011; Kamen, 2010). However, these thresholds have been observed to change due to resistance training, which affects the sum of the motor pool engaged in the contraction. Decreased recruitment thresholds have been seen in the tibialis anterior following isometric strength training after four weeks (Del Vecchio et al., 2019), and chronic resistance-trained individuals appear to have lower recruitment thresholds for the biceps brachii when compared to untrained participants (Pearcey et al., 2014). Contrary to this, Sterczala et al. (2020) found no change in recruitment thresholds of the motor units within the vastus lateralis after eight weeks of intensive resistance training when hypertrophy of the muscle fibres within the motor unit is considered. Although decreases in these larger motor unit recruitment thresholds is a generally accepted adaptation from strength training, difference in methodology and exercise intensity between studies make it difficult to draw decisive conclusions (Elgueta-Cancino et al., 2022). When interpreting SEMG signal amplitude, individual differences in recruitment thresholds, heterogeneity in motor unit size, speed of movement, and possible fatigue effects should be considered, particularly when investigating the reliability and impact of movement on muscle excitation.

2.1.2 Motor Unit Firing Frequency and Synchronization

Increases in muscle force after full recruitment of the motor unit pool, particularly above intensities higher than 85%, are believed to be primarily due to increases in rate coding or discharge rates of the fully recruited motor unit pool (Duchateau et al., 2006). These adaptations have been seen to occur during both isometric, ballistic, and dynamic resistance training. Del Vecchio et al. (2019) examined the effect of 12 training sessions of 40 ballistic contractions and 30 sustained isometric contractions performed at 75% of maximum effort on maximal and submaximal isometric contractions. After four weeks of the training regime, motor unit discharge rates increased during the plateau phase of the ramp isometric contraction performed at 70% maximal voluntary isometric contraction (MVIC). This finding aligns with increases in firing rates during rapid contractions of the biceps brachii for similar torque

production (Reece et al., 2021). However, it differs from slower ramp isometric contractions, where no changes were observed in motor unit firing rates (Reece et al., 2021).

Initial increases in strength and higher normalized SEMG in untrained participants appear to be related to changes in motor unit firing rate and recruitment when training at loads greater than 60% of maximum strength but are not seen in training loads at 30% (Jenkins et al., 2017). Although strength-trained individuals overall show higher muscle excitation during maximal tasks, submaximal tasks for the same relative load have lower excitation and decreased motor unit recruitment thresholds and firing rates. This decreased neural drive for the same relative load results in a more efficient muscular response to force generation (Santos et al., 2023). While trained participants retain their early increases in muscle excitation but show lower increases in the neural drive after initial adaptations, later strength gains are believed to result more from muscular adaptations related to hypertrophy (Pearcey et al., 2021). However, highly skilled field athletes have shown increases in SEMG amplitude and faster rates of SEMG development during rapid isometric knee extensions compared to non-athlete controls (Judge et al., 2003). Unfortunately, this study did not disclose the participants' previous training history, so it is unclear if a relearning effect may have occurred in response to re-initiated strength training after a period of inactivity.

Motor unit discharge rates have increased by 15% during maximal contractions in young adults and by 49% in older adults after six weeks of traditional strength training but not from contractions at 10% and 50% of MVC. (Kamen & Knight, 2004). In addition, motor unit firing rates have been observed to fluctuate during different times of the day (Hirono et al., 2024), which may add a circadian confounding effect. Other factors, such as training to failure or stopping the work set several repetitions before failure also appears to affect motor unit discharge rates. Ruple et al. (2023) found that motor unit discharge rates increased when resistance training for the vastus lateralis was carried to failure. However, despite similar training volumes, no change was observed in lower threshold motor units when training was stopped short of failure.

These findings contrast with Hester et al. (2016), where increases in peak torque were not associated with increases in motor unit firing rates. The researchers found no significant differences in firing rates versus recruitment threshold for the vastus lateralis after training with four sets of ten maximal concentric isokinetic contractions three times a week. However, this study used SEMG decomposition methods and could not identify individual motor units. A similar type of response was also observed from three weeks of isometric training consisting of three sets of ten maximal contractions. This type of training resulted in no changes in average motor unit firing rates of both higher and lower motor units (Pucci et al., 2006). Regarding the longitudinal effects of resistance training on firing rates between trained and untrained participants, a study by Casolo et al. (2021) found that motor unit discharge rates and recruitment thresholds in the biceps brachii did not differ when normalized to the cross-sectional area.

In a detailed review examining the effect of resistance training on motor unit firing properties, Elgueta-Cancino et al. (2022) concluded that there is no change in motor unit discharge rates following resistance training. This conclusion comes from the combined fact that there are high levels of heterogeneity among studies and limited high-quality research, making inferences difficult. These issues were also echoed by Herda (2022), where motor unit changes in discharge rate were thought more likely not to occur despite earlier research suggesting the opposite due to methodological issues that failed to account for changes in action potential amplitudes, decreases in recruitment thresholds, and differences in study design.

Synchronization of motor units can also affect the combined motor unit action potentials (MUAP) and SEMG amplitude (De Luca, 1997). This increase in motor unit synchronization has been observed when generating higher forces (Oliveira et al., 2022). Although earlier research has suggested that motor unit synchronization may be a trained adaptation to resistance training (Milner-Brown & Lee, 1975), more recently, its contribution to overall force production is not believed to be functional (Farina & Negro, 2015) although it may play a role in the rate of force production in ballistic contractions (Semmler, 2002) and force steadiness (Taylor et al., 2003). To conclude, although there is extensive literature

assessing firing rates and motor synchrony in a wide variety of conditions, the current view is that these neural adaptations do not significantly contribute to the SEMG amplitude during traditional strength training movements.

2.1.3 Cortical and Subcortical Changes

The cortex, subcortex, and spinal cord interact to generate and transmit the necessary nerve impulses to the neuromuscular junction. This neural signal excites the motor unit, which causes muscle activation and creates movement. Resistance training increases corticospinal excitability due to changes within the primary cortex and subcortex (Siddique et al., 2020). Neural adaptations have been detected in the corticospinal pathway after four weeks of resistance training involving the first dorsal interosseus muscle of the hand, resulting in a lower electromyographic response for the same torque (Carroll et al., 2002). This increase in excitability combined with decreased inhibition in the motor cortex is believed to be related to a motor learning effect that occurs from repeated movements, resulting in increased strength and performance (Škarabot et al., 2021). As suggested initially by Sale (1988), the initial and longer-term increases associated with strength seen in this context would suggest that maximal strength may be related to the development of learning to execute the movements in a skilled manner in combination with muscle hypertrophy and peripheral neural adaptations (Behm, 1995). Therefore, the influence of the corticospinal pathway and the efficiency of the necessary muscle synergies during the desired movement may also contribute to the SEMG amplitude of a specific involved muscle.

2.1.4 Summary of Neural Adaptations from Resistance Training

As previously discussed, multiple factors can affect the neural drive to the involved muscles during movement. Cortical and subcortical adaptations in excitability, motor unit recruitment, firing rates, and the degree of motor unit synchrony have been investigated in the literature in response to resistance training. Table 1 provides a summary of these contributing factors and outlines general adaptations that have been observed in the literature.

Table 1. Summary of Neural Adaptations from Resistance Training (RT)

Neural Adaptation	Training Result
SEMG Amplitude	Initial rapid ↑ in SEMG, then modest increases thereafter (Carroll et al., 2001; Folland & Williams, 2007). ↓ SEMG response to similar load during training (Santos et al., 2023) Detraining: concentric SEMG ↓ after 3 months, eccentric SEMG ↔ (Andersen et al., 2005)
Motor unit recruitment (MUR)	↑ in an orderly manner from smallest toward larger MU (Henneman et al., 1965, Riek & Bawa, 1992; Sale, 1988) Full MUR in movements up to 80-90% of MVC in large muscle groups (Kukulka & Clamann, 1981, De Luca et al., 1982, Cutsem et al., 1997). Lower for the hand muscles General consensus of ↓ recruitment thresholds of larger motor units (Del Vecchio et al., 2019, Pearcey et al., 2014)
Firing rates (FR)	Inconclusive (Elgueta-Cancino et al. , 2022) or ↔ (Herda, 2022) for slow controlled submaximal training. ↑ in larger motor unit FR during ballistic movement and maximal contractions (Del Vecchio et al., 2019, Reece et al., 2021). ↑ in smaller motor unit FR when training is carried to failure (Ruple et al. 2023) > ↑ in FR in older adults than younger adults after maximal contractions but not submaximal contractions (Kamen & Knight, 2004). > ↑ in FR at midday vs morning (Hirono et al., 2024)
Cortical and Subcortical Changes	↑ corticospinal exciteability (Siddique et al., 2020) ↓ corticospinal inhibition (Skarabot et al., 2021) Strength performance may be more skill oriented (Sale, 1988; Behm, 1995)
Motor Synchrony	Although observed, is not believed to be functional during controlled movements (Farina & Negro, 2015) May play a role in ballistic movements (Semmler, 2002) and force steadiness (Taylor et al., 2003)

RT = resistance training. FR = firing or discharge Rates. MU = motor units. MUR = motor unit recruitment. ↑ = increased. > ↑ = greater increase. ↓ = decreased. ↔ = no change.

2.2 Use of Bipolar SEMG in Exercise Selection

Muscle contraction results from a neuroelectric signal generated in the motor cortex that travels down efferent neurons to the motor units of the target muscle. This signal causes the muscle fibre membrane to depolarize, activating the muscle (Merlo & Campanini, 2010; Rainoldi et al., 2016). This summation of action potentials is often referred to as neural drive (Farina et al., 2014). In the case of SEMG, the motor unit action potential (MUAP) that is generated within the muscle is then conducted

through the muscle tissues, intramuscular and subcutaneous fat and fluid, and the skin to which a bipolar electrode configuration is attached (Kamen, 2010). Bipolar SEMG (the combination of two monopolar electrodes separated by a minimal distance to record the differential of the MUAPs) is common in many muscle activation studies due to the increased ability to reduce common mode noise and crosstalk with adjacent muscles (Bhullar et al., 1990; Merletti & Muceli, 2019) and general better reliability compared to monopolar surface electrodes (Stock et al., 2010). The recorded signal is then amplified, filtered, and processed using a variety of electronic hardware, computer software, and mathematical techniques for further analysis and interpretation (Winter, 2009).

Interpreting the SEMG signal can be challenging during isometric and particularly dynamic contractions (Farina, 2006). This result is partially due to the multiple factors that can affect the SEMG signal, as previously described. Surface electrode location is a primary concern in collecting accurate and reliable results during dynamic contractions, as the innervation zone can move relative to the electrodes. This movement can affect the signal's amplitude, in addition to the fact that different locations may represent different pools of motor units within the target muscle (Mesin et al., 2009). The SENIAM project has addressed many of these concerns through recommendations for surface electromyography applications in research and clinical settings (Merletti, 2000). For example, for the biceps brachii, it is recommended that electrodes be placed 20 mm apart and placed below the innervation zone at one-third the distance between the medial acromion and the cubital fossa in line with the muscle fibres (Hermens et al., 2000).

SEMG amplitude results from the combined MUAPs within the electrode detection area (including possible crosstalk with nearby muscles), the firing rate of the motor units, motor unit synchrony, and tissue and spatial filtering effects (Kamen, 2010). Signal processing of SEMG in studies involving comparisons of dynamic contractions, including resistance training exercises, typically involves initial filtering, calculating the root mean square (RMS) of the signal with a 100 ms moving window (Hägg et al., 2005; Saeterbakken et al., 2019; Solstad et al., 2020; Uysal et al., 2022) and then normalizing to either

an MVIC or submaximal contraction to improve reliability due to inter-individual differences in absolute neural activity (Sousa et al., 2012). RMS is a popular choice in SEMG signal processing due to the general linearity of the signal to force production and the belief that it is representative of the physiological activity during contraction (Fukuda et al., 2010). SEMG amplitude results can then relate to ranking various exercise movements on muscle activity to target a specific muscle or muscle group.

2.3 Classification of Intra-class Correlation

The intra-class correlation coefficient (ICC) is a statistical method used to examine the variance between participants relative to the total variance of all participants, expressed as a ratio from 0 to 1, to measure consistency or reliability across different periods (Schober et al., 2021). It is important to note the differences in the classification of the ICC. Fleiss (1999) proposed a reliability level scale where less than 0.4 represents poor reliability, 0.4 to 0.75 represents fair reliability and values above 0.75 for excellent reliability. In contrast, Richman et al. (1980) suggest that ICC values less than 0.6 be considered questionable, 0.60 to 0.80 as moderate reliability, and values greater than 0.80 as high. Koo and Li (2016) have also suggested ICC ranges similar to Richman et al. (1980), with values less than 0.5 representing poor reliability, moderate reliability between 0.5 and 0.75, between 0.75 and 0.9 for good reliability, and any values above 0.9 as excellent when heterogeneous samples are greater than 30 with more than two raters. However, defining a good ICC value is difficult without considering the standard error of measurement (SEM) and the minimal differences required for confidence that a change has occurred (Weir, 2005), as well as measurement agreement and variability among the samples of the participants (Koo & Li, 2016). Specific studies that classify good reliability using the recommendations proposed by Fleiss (1999) would be questionable using the scale defined by Richman (1980). As between-participants variability can affect the ICC, one should also consider the SEM, minimal difference, and the ICC together to interpret reliability as the SEM is unaffected by this variability (Weir, 2005)

2.4 Inter-day Reliability of Surface Electromyography in Dynamic Movements

Although many studies have examined the effect of different resistance training exercises on SEMG activation, literature investigating the inter-day reliability of the SEMG amplitude has shown significant variability that appears dependent on the movement kinematics and the specific muscles involved. Ball and Scurr (2010) found good reliability in absolute SEMG values for the triceps surae (typical error measurement (TEM) = 8.9-14.5%) both between days and weeks in the squat jump, acceptable reliability for medial gastrocnemius (TEM = 12.9-14.5%) during the sprint and isometric assessment, but poor reliability (TEM = 17.4-24.7%) for the lateral gastrocnemius muscle group during isokinetic plantar flexion across all velocities. Contrary to this, other studies have found poor reliability for the gastrocnemius (ICC = 0.01) and biceps femoris (ICC = 0.24) during dynamic contractions between sessions involving maximal counter-movement vertical jumps (Goodwin et al., 1999) and for the gastrocnemius during single leg hopping (Spearman-Brown reliability coefficient (SB) = 0.56), running, (SB = 0.47) and drop jumps (SB = 0.29) tasks separated by one week (Gollhofer et al., 1990). Poor reproducibility during these ballistic movements may be due to the involvement of the stretch reflex which can influence neuromuscular activity in the muscles involved (Gollhofer et al., 1990; Goodwin et al., 1999). However, other investigations examining between-session reliability of SEMG amplitude for lower body dynamic contractions when the stretch reflex is minimized have also found poor to moderate inter-day results for the vastus muscles in the lateral step-up (ICC = 0.06–0.67) (Worrell et al., 1998) and during cycling (Coefficient of Variation (CV) = 15.8-38.1%) at submaximal intensities (Jobson et al., 2013). In examining the inter-day SEMG amplitude reliability of the muscles that act on the hip joint during isokinetic movements, Claiborne et al. (2009) found high bilateral reliability (ICC = 0.81-0.95) for twelve of the eighteen muscles identified as the prime movers, while the rest had moderate reliability (ICC = 0.50-0.76) during the concentric motions of hip abduction, adduction, flexion, extension and internal and external rotation. Eccentric contractions showed similar high reliability (ICC = 0.82-0.95) across the involved muscles except for the adductor muscle (ICC = -1.46) and the medial hamstring of the left leg (ICC = 0.42) during internal rotation.

The muscles of the upper body have also shown wide variation in reliability. Zandi et al. (2018) examined the repeatability of SEMG readings using the ICC and SEM for the upper arm and shoulder muscles during the volleyball overhead throw. The study involved university-level volleyball players who were each instructed to hit a volleyball hanging from the ceiling as hard as they could in a forward direction. Results showed lower moderate inter-day reliability (ICC = 0.68-0.93 vs ICC = 0.85-0.99) and higher absolute SEM (SEM = 1.28-5.15 vs SEM = 0.75-4.38) than repeated tasks performed on the same day. However, contrary to the previously mentioned studies, inter-day SEMG amplitude reliability was good for the anterior deltoid (ICC = 0.94) and vastus lateralis (ICC = 0.93) during the bilateral front raise and squat (Sorbie et al., 2018). To amplify this incongruity in the literature, Youdas et al. (2010) assessed SEMG reliability across multiple upper body muscles in three variations of a pull-up exercise over two sessions separated by two weeks. Moderate reliability was determined for the biceps brachii (ICC = 0.64) and lower trapezius (ICC = 0.64), but poor reliability coefficients for the external oblique (ICC = 0.57), erector spinae (ICC = 0.48), latissimus dorsi (ICC = 0.35), and pectoralis major (ICC = 0.35).

Based on the previous studies, increased velocity in movements involving multiple joints appears to result in less predictable SEMG amplitudes across sessions due to several neuromuscular and load-sharing strategies adopted by the individual. When these strategies are minimized by using electrically invoked contractions, SEMG reliability is excellent for the biceps brachii (ICC = 0.96-0.98) (Calder et al., 2005) but less reliable for the vastus medialis (ICC = 0.28-0.52.2) and tibialis anterior (ICC = 0.78-0.81) (Merletti et al., 1995, 1998). In summary, it appears that SEMG amplitude during dynamic movements overall has moderate reliability during slower, less complex movements, and reliability may be dependent on the muscle itself due to unique recruitment strategies and morphological structure.

Isometric contractions are often used to normalize the SEMG signal, allowing comparisons across time periods and between individuals and groups (Sousa et al., 2012). In comparison to dynamic contractions, isometric contractions show higher reliability and repeatability. Singla et al. (2018) found good to excellent inter-day values for normalized SEMG values of the upper arm muscles (ICC = 0.84-

0.98). In support of this finding, De Araújo et al. (2009) found excellent reliability for intra-day (ICC = 0.78 - 0.99) and good to excellent values (ICC = 0.52-0.98) for inter-day reliability for all involved muscles. In both these studies, SEM was also lower for intra-day sessions than inter-day sessions. Both within and between day isometric contractions have generally shown moderate to excellent reliability in the vastus medialis (ICC = 0.90 – 0.92) (Spudić et al., 2020), scapular musculature (concentric phase ICC = 0.87-0.98, eccentric phase ICC = 0.65-0.97) (Grime et al., 2018), quadriceps (ICC = 0.59-0.98) (Larsson et al., 1999; Mathur et al., 2005) and biceps brachii (ICC = 0.92-0.99) (Howatson & Van Someren, 2005).

To summarize the work above, intrasession or within-day comparisons of SEMG amplitudes appear more reliable than inter-day sessions separated by several days or more. SEMG amplitudes resulting from higher force contractions are also more reliable than lower force contractions. Muscle activation during dynamic contractions during test-retest scenarios involving several days is consistently less reliable than isometric contractions. Notably, isokinetic and ballistic SEMG amplitudes are less reliable than isotonic movements performed at a slower execution. These differences in inter-day reliability appear to depend on specific muscles and movement kinetics and kinematics.

2.5 Other Factors Affecting Inter-Day Reliability of SEMG Amplitude

As previously discussed, electrode placement relative to the innervation zone can affect the absolute SEMG amplitude. However, normalizing the signal to an isometric or dynamic MVIC helps to allow direct comparisons of muscle contractions between sessions (Besomi et al., 2020). Geometrical factors of the assessed muscle fibre regarding pennation angle, motor unit location, tendon insertion, and innervation zone location can be different between individuals (Kamen & Caldwell, 1996; Neyroud et al., 2015; Rainoldi et al., 2000), thus increasing the variance between participants within the group and thereby affecting the inter-day reliability.

Performing movements at different velocities can also affect SEMG amplitude (Fan et al., 2014), with higher and lower angular velocities producing greater and lower amplitudes during concentric and

eccentric movements, respectively (Potvin, 1997). Decreased motor unit recruitment thresholds during dynamic contractions as compared to isometric contractions in the biceps brachii, along with changes in firing frequency between concentric and eccentric contractions, can also contribute to the differences in the MUAPs during elbow flexion at different angular velocities (Kossev & Christova, 1998; Tax et al., 1990). In addition, restrictions on movement task execution, such as controlling for velocity movement, can affect individual recruitment strategies that can alter the SEMG signal (Crouzier et al., 2019). This variation is partially related to an individual's synaptic efficiency and unique electrophysiological characteristics of the active motor unit thresholds as determined by intracortical facilitation and inhibition (Orth et al., 2003). The exact cause of this neural adaptation in resistance training remains unclear but appears to result from changes in the cortical and subcortical levels of movement control (Škarabot et al., 2021).

Most movements are a result of multiple muscles acting across multiple articulations. The reliability of these coordination patterns, or muscle synergies, varies depending on the task, the muscles involved, and the expertise of individuals during movement (Taborri, Agostini, et al., 2018). The extraction of muscle synergies has shown to have muscle-specific interindividual variability but good to excellent reliability for neuromuscular coordination strategies through a wide variety of ordinary (Taborri, Palermo, et al., 2018) and exercise-related movements such as the bench press (Kristiansen et al., 2016), power clean (Santos et al., 2021), and cycling (Hug et al., 2010). As athletes become more skilled in acquiring complex movement patterns, interindividual differences in muscle synergies appear to narrow (Frère & Hug, 2012; Kristiansen et al., 2015; Santos et al., 2021). Similarly, Soylu et al. (2006) found increased repeatability in EMG linear envelopes in elite archers compared to beginners and non-archers. However, contrary to the previous studies, Turpin et al. (2011) found that rowing expertise did not alter muscle synergies or motor coordination patterns. In this case, improved rowing performance was possibly related to how the trained rowers altered their mechanical output using already established muscle synergies.

2.6 Inertial-based Motion Capture

Controlling for variability in movement kinematics is crucial when comparing SEMG amplitude signals across days in individuals, as changes in angular velocity may impact this relationship. With technological advancements in inertial measurement units (IMU), the ability to record and analyze movement in the field is now possible with generally good to excellent reliability and acceptable accuracy and precision depending on the system, the number of IMUs involved, and the assessed movement (Clemente et al., 2022; Mobbs et al., 2022). IMUs record data along three orthogonal axes for linear acceleration, angular velocity, and strength and direction of the surrounding magnetic field using an onboard accelerometer, gyroscope, and magnetometer. Although sensor drift and magnetic field disruptions can affect accuracy (Young, 2010), solutions using sensor fusion algorithms can be implemented for more consistent results in orientation by adjusting for magnetic disturbances, temporal shifts in alignment due to noise, and sensor sensitivity (Chen et al., 2020). Additional calculations to rotate the sensor's reference frame relative to the global reference frame can allow for more accurate kinematic information for the specific movement.

Multi-sensor IMU systems can have acceptable to excellent accuracy for monitoring multi-joint kinematics during lower-body (Al-Amri et al., 2018) and upper-body movements (Sers et al., 2020). However, the use of a single IMU can be more practical and is reliable in capturing movement parameters for jumping (McHugh et al., 2019), walking (De Ridder et al., 2019), pathological conditions (Vítečková et al., 2020), recognizing soldier movements and calculating survivability (Mavor et al., 2023), and during the "Timed Up and Go" test (Kleiner et al., 2018).

2.7 Summary

Resistance training enhances muscle strength through changes in the nervous system and muscle fibre hypertrophy. More specifically, as greater forces are required, increased neural drive as measured by SEMG amplitude results from a combination of increasing MU recruitment from smallest to largest MUs, decreased recruitment thresholds of larger MU, changes in motor unit firing frequency, and partly from

motor unit synchronization, particularly during ballistic contractions. These changes are essential for activating the necessary muscle tissue required for force production, which, over time, leads to morphological changes like increased muscle fascicle length, pennation angle, and greater cross-sectional area. These changes are observed across both sexes and all age groups and are most prominent in untrained participants during the initial period of resistance training routines. However, inconsistencies exist in the literature on the impact of firing rates and synchronization of motor units on force production from traditional resistance training. The overall consensus suggests that these neuromotor changes do not significantly contribute to increases in strength performance. Enhanced corticospinal excitability and reduced cortical inhibition, combined with improved motor learning, which forms efficient movement patterns, are believed to be the main factors affecting force production.

SEMG amplitude reliability varies with movement complexity and speed in dynamic movements. Simple, slower dynamic movements are more reliable than faster, ballistic, and complex movements involving multiple muscle groups. Same-day measurement is more reliable than inter-day measurement, which may be due to factors such as electrode placement, muscle morphological characteristics, individual motor unit recruitment strategies, and speed of movement. IMUs offer a way to accurately capture this movement in a non-restrictive method to enhance the study of muscle excitation and the resultant movements.

As mentioned in the introduction, this thesis aims to evaluate if the relationship between normalized SEMG amplitudes of the biceps brachii during four resistance arm curl exercises changes over four different exercise sessions separated by several days. In prescribing exercise routines that result in predictable adaptations to increase strength and muscle hypertrophy, clinicians assume that a particular exercise produces a consistent stimulus to the target muscle during the prescribed training cycle that may last several weeks to months. Although measured SEMG amplitude appears to have moderate to good reliability during controlled movements, it remains to be determined whether a chosen exercise would maintain the same magnitude or rank over similar exercises through multiple training sessions. Studying

the reliability of exercise choice based on normalized SEMG amplitude would provide insight into its consistency over time and support its potential as a proxy for longitudinal adaptations.

CHAPTER 3: METHODS

3.1 Participants

Eight trained (5 males and 3 females) and 7 untrained (4 males and 3 females) participants with a mean age of 37.1 years (SD = 15) from the Ottawa area were recruited to participate in this study. Detailed demographics are presented in Table 2. The operational definition of trained was defined as currently, or within the past two weeks, having performed a resistance training routine for the upper body. The operational definition of untrained was defined as not performing an upper body resistance training routine in the past six months. All participants were considered healthy as determined by the GET ACTIVE questionnaire (Canadian Society for Exercise Physiology, 2017; Appendix A) and were free from any musculoskeletal and neuromuscular disorders, concussions within the past year (even if clinically recovered), illness, or other medical condition that would limit the safe and proper execution of the exercises. Participants were asked to maintain their normal activity levels (training volumes and intensity or untrained status) throughout the collection period. Informed consent was obtained from all the participants before participating in the study (Appendix B). All participants completed the study without experiencing any adverse health conditions or injuries.

Table 2. Participant Demographics

Participant	<i>n</i>	Age (years) Mean (SD)	Peak Force (N) Mean (SD)	SS (mm) Mean (SD)
Female (Trained)	3	29 (17.3)	130.8 (2.8)	35.7 (9.7)
Female (Untrained)	3	36.3 (14.2)	108.1 (12.4)	56.3 (15.9)
Male (Trained)	5	31.6 (16.4)	235.9 (27.9)	25 (4.4)
Male (Untrained)	4	50.5 (1)	192.7 (29.8)	25.6 (4.9)
All	15	37.1 (15)	178.8 (56.8)	33.6 (14.7)

SD = standard deviation. *n* = sample size. SS = Sum of four skinfolds (Deltoid, Brachioradialis, Biceps, and Triceps). N = Newtons.

3.2 Consent

Before any data were collected, this project was first reviewed and approved by the University of Ottawa's ethical review board (Appendix C). Before taking part, participants were allowed to ask questions regarding their involvement and were then asked to review, complete, and sign an informed consent form (Appendix B) and a health screening questionnaire (Appendix A).

3.3 Study Design

Data collection took place over five separate sessions, with the first session separated from the second session by three days (± 1 day) and the subsequent sessions following the second session separated by four days (± 1 day). The time between sessions allowed for hypothetical complete muscle and neural recovery between sessions and provided flexibility to the participant for scheduling. The time between sessions can be found in Table 3. A qualified and experienced clinical exercise physiologist supervised all sessions.

Table 3. *Timing of data collection sessions*

Time between sessions	<i>n</i>	Days (Mode)	Max-min (Range)
Session 1 and 2*	15	4	5-2 (3)
Session 2 and 3	15	3	4-3 (1)
Session 3 and 4	15	4	5-3 (2)
Session 4 and 5	15	3	5-3 (2)

* - One participant required 5 days between session one and two due to a scheduling issue.

3.4 Location of Collection

Participants were allowed to perform the sessions from their chosen location, provided the area was safe, adequately private, free of obstacles, and in a comfortable environment (between 18 and 24 degrees Celsius at 40% to 60% relative humidity). Three sessions of the necessary 75 sessions for all 15 participants (15 participants multiplied by five sessions each) were performed at the participant's residences. The sessions not conducted at the participant's residence took place at a private facility. Exercise equipment was provided and transported along with the necessary data collection instruments to the location if necessary.

3.5 Session One: Exercise Familiarization and Strength

The first session was a familiarization session for the participants to determine the maximal isometric strength of the dominant arm flexors, to have an opportunity to practice the required exercise movements for proper technique and tempo, and to ask any questions related to their participation. The biceps brachii was chosen as the muscle to investigate as it is a commonly perceived visual indicator of strength and is popular in targeted training routines. According to Google Trends (2023), search volume for the term “biceps workout” receives approximately 50,000 searches every month worldwide. The biceps brachii is a biarticular two-headed fusiform muscle that attaches proximally at the tip of the coracoid process (short head) and the supraglenoid tubercle (long head) of the scapula (Moore, 1992). Distally, it attaches to the tuberosity of the radius and bicipital aponeurosis and serves to flex and supinate the forearm (Moore, 1992). Recording the SEMG signal from this muscle is convenient due to the relative ease of electrode placement for the participant, generally lower subcutaneous tissue between the skin and the muscle, reduced risk of crosstalk, and the longitudinal and parallel alignment of the muscle fibres to the humerus (Criswell, 2010). In addition, even those with minimal resistance training backgrounds have most likely exercised this muscle through various arm curl exercises.

The first session aimed to reduce the neuromuscular learning effects of performing a potentially novel arm exercise at a fixed tempo or unfamiliar cadence. The participant's choice of arm to throw a ball determined the dominant arm. The performance of a unilateral arm exercise is to minimize potential cross-education effects (Manca et al., 2017). The familiarization session began with demonstrating the proper exercise technique for the arm curl exercises, specifically, the dumbbell curl, hammer curl, incline curl, and concentration curl, as shown in Figure 1.

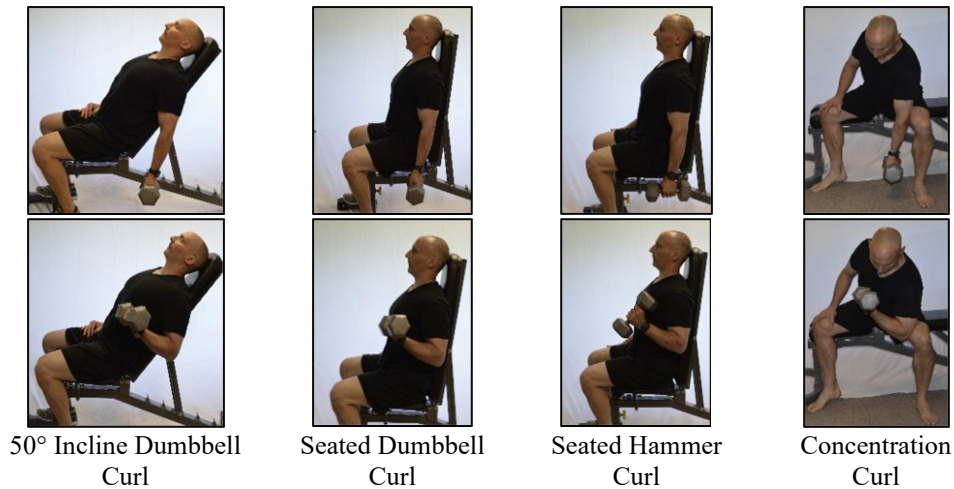


Figure 1. The top and bottom figures represent the start and finish positions, respectively.

Participants were allowed to practice the movements to the required tempo of 0.5 Hz (30 beats per minute) by a digital metronome (EUMLab & Polybeat PTE Ltd., 2023) played on a tablet (iPad Pro, Apple Inc., Cupertino, California, 2018). More specifically, the participants were asked to keep time with the metronome so that both the concentric and eccentric portions of the repetition were 2 seconds in length, with no pause at the top of the movement and a 2-second pause between repetitions. The tempo was chosen to allow a slow and controlled exercise performance as recommended for resistance training (Haff & Triplett, 2016) and minimize momentum's effect on force production. In addition, controlling execution tempo standardizes the kinematics as much as possible throughout the four trials.

Proper exercise technique was assessed and corrected specific to the participant as to the criteria described in Croskery (2004). All exercises were performed unilaterally with the dominant arm. In general, for all exercises, the following was considered improper technique: arching of the back to complete a repetition, movement of the elbow forwards or backwards as the weight is lifted or lowered, a slouching posture where the chest drops and the upper back rounds, swinging of the dumbbell to complete a repetition, switching to a different hand position (for example from a supinated grip to a neutral grip)

during the performance of the exercise, failure to bring the dumbbell close to the front of the shoulder at the top portion of the repetition, or fully return to the original starting position.

Incline curl (INCL) had the participant sit with their knees together on an incline bench set at an angle of 50° to the floor. The exercising upper arm was approximately perpendicular to the floor while holding the dumbbell in an underhand, supinated grip. While keeping the upper arm and elbow stationary and the hand supinated, the dumbbell was raised upwards by bending the arm at the elbow following the natural curve of the arm movement. Dumbbell curl (DBELL) and hammer curl (HAMM) were performed in an upright seated position following a similar arm movement to the INCL while maintaining the dumbbell in a supinated and neutral grip, respectively. For concentration curl (CONC), the participant was seated perpendicular to the bench with feet placed wider than shoulder width. At the same time, the elbow was pressed firmly into the medial side of the thigh, just beside the knee, while holding the dumbbell with a supinated grip.

After the familiarization session, a maximal voluntary isometric contraction (MVIC) to determine the strength of the elbow flexors of the dominant arm was obtained using a single handle attached to a force gauge (Mark-10 Series 3, Mark-10 Corporation, Copaugue, New York) secured to the base of the bench (Figure 2).



Figure 2. Apparatus to measure MVIC elbow flexor force production and SEMG amplitude for normalization for the biceps brachii.

The participants performed a five-second MVIC for the dominant arm with the elbow flexed at 90 degrees while seated on an exercise bench (A2, Bonvork Fitness, US) for three attempts using a supinated grip. Each attempt was separated by three minutes of rest to allow for adequate recovery and participants were verbally encouraged to generate as much force as possible.

Approximately one-third of the average force generated, as determined by the average of a one-second window around the peak of the MVIC, was used to calculate the submaximal load for all arm curl exercises. Due to the inability to precisely match the load to one-third of the maximum force produced, the closest working load was chosen by rounding up or down to the nearest dumbbell. For example, if the desired load is 5.9 kg, a dumbbell weight of 5.4 kg was chosen as the prescribed load (Table 4). One participant required the next lower working weight other than the original prescribed load due to the inability to follow proper form at the designated weight for the INCL.

Table 4. Prescribed load calculations from MVIC force (N)

Prescribed Load (kg)	MVIC Low Range (N)	MVIC Upper Range (N)
1.4	26.75	53.51
2.3	53.52	80.26
3.2	80.27	100.33
3.7	100.34	120.40
4.5	120.41	147.15
5.4	147.16	180.59
6.8	180.6	214.04
7.7	214.05	247.48
9.1	247.49	280.92
10	280.93	314.37

Due to slight variations in individual dumbbell weights, all working loads chosen for the arm curl exercise were within 250 g of the prescribed load. N = Newtons.

3.6 Sessions Two through Five

For sessions two through five, the participants wore an IMU sensor (G-Sensor 2, BTS Spa, Milan, Italy) secured to the back of the wrist of the exercising arm with a self-adhering adjustable strap along with four SEMG sensors placed on the brachioradialis, biceps brachii, anterior deltoid, and triceps brachii. Surface EMG locations for the brachioradialis, biceps brachii, anterior deltoid, and the long head of the triceps brachii were first marked with a surgical marker as determined by SENIAM standards (Hermens

et al., 2000), while brachioradialis placement was by Criswell (2010). Specifically, locations for the SEMG sensors were as follows: one-third of the length along the line from the cubital fossa and medial acromion process (for the biceps brachii), one finger width distal and anterior to the acromion along the direction of the line between the acromion and the base of the thumb with the palm facing inwards (anterior deltoid), 50% along the line and two finger widths medially between the olecranon and posterior crista of the acromion (long head of the triceps brachii), and approximately 4 cm distal from the lateral epicondyle on the medial fleshy mass of the brachioradialis along the line between the lateral epicondyle and styloid process of the wrist (Figure 3).

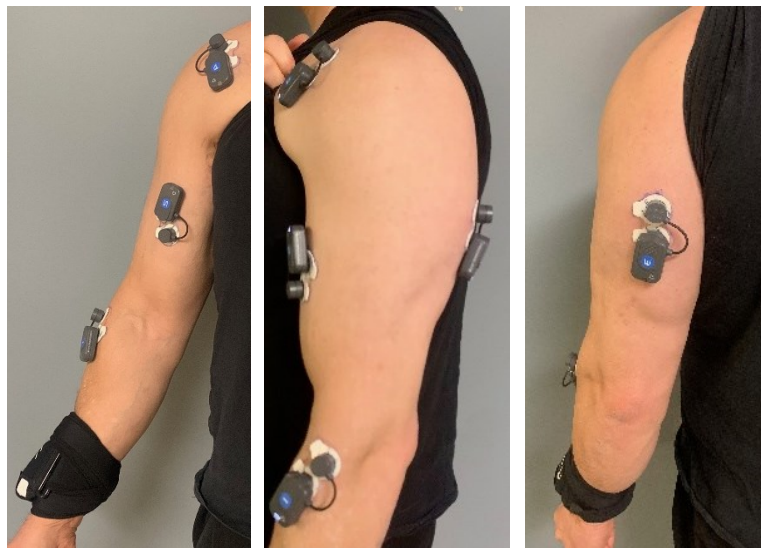


Figure 3. Anterior, lateral, and posterior views of SEMG and IMU sensor placement.

Skin preparation included lightly abrading the area using NuPrep skin preparation gel (Weaver and Company, Aurora, Colorado) and de-oiling with an alcohol swab. Next, a pair of Ag-CI SEMG electrodes (H124SG, Covidien, Gosport Hampshire, United Kingdom) with an interelectrode distance of 25 mm were placed on the previously marked locations. Once the sensors were attached, signal strength for the anterior deltoid, biceps brachii, brachioradialis and triceps brachii was confirmed by asking the participant to flex at the shoulder and elbow and extend at the wrist and elbow, respectively.

Following the attachment of the SEMG sensors and securing the IMU to the wrist, the participants were asked to take a seated position on the exercise bench and perform a light warm-up at the proper tempo for each of the exercises for three to five repetitions at approximately 50% to 75% of the

exercise load depending on the closest available dumbbell weight. The participants rested for three minutes before starting the data collection. Each session's exercise performance sequence was randomly selected using an online list randomizer (Haahr, 2024). To ensure the robustness of the randomization process, the third generated list was selected for use. This approach was chosen to mitigate any potential bias that might arise from the initial randomization attempts. The participant rested approximately three to five minutes between the performances of each exercise to allow adequate recovery between attempts.

In order that the MVIC collection did not result in additional fatigue on exercise performance, three MVICs for the brachioradialis, biceps brachii, triceps brachii, and anterior deltoid (arm flexion at an elbow angle of 90 degrees with the hand first in a pronated position then supinated, arm extension at an angle of 90 degrees with the hand in a pronated position, and shoulder flexion at an angle of 90 degrees with the hand in a neutral position, respectively) were performed while remaining seated on the exercise bench after the completion of the exercises. For each arm position, participants were instructed and verbally encouraged during the performance to generate as much force as possible for three attempts against manual resistance provided by the investigator. Each MVIC lasted approximately 3 seconds and was separated by one minute of rest (Sousa et al., 2012). Following the MVIC collection, an outline of the electrodes was recorded on the skin using a surgical marker to record the exact placement of the electrode for future reassessment. Through previous testing, the marker ink was seen to last approximately five days under regular hygiene practices.

As the interface between the electrode and skin can affect impedance and thus the SEMG amplitude (Clancy et al., 2002), a measurement of electrode-to-electrode impedance was recorded using an auto-ranging multimeter (Mastercraft, Canadian Tire, Canada) by connecting the probes to the electrode snap connectors after data collection was complete. Considering that the thickness of the layer of subcutaneous fat can act as a low pass filter and affect the SEMG amplitude (Nordander et al., 2003) as well as skin impedance, a skinfold thickness measurement was taken with callipers (Lange style, Jamar, US) at each electrode site after the SEMG sensors and electrodes were removed. Before performing the

exercises, a visual analog scale (Appendix E) adapted from Lee et al. (1991) and as described by Cleather & Guthrie (2007) was administered to monitor fatigue and soreness between sessions. Briefly, participants were asked to place a vertical line on a 90mm horizontal line to indicate their interpretation of their current overall level of cognitive and physical fatigue (from not tired at all to extremely tired) and muscle soreness (no pain to unbearable pain). A 90mm line was used due to the formatting of the printed document. The placement of the vertical line was then translated into a rating from 0 to 100 by dividing the distance of the marked line from the start in mm divided by 90mm, representing a ratio of minimum to maximum values.

3.7 Data Analysis

Kinematic and SEMG Data were collected by native software using EMGAnalyzer (Version 2.10.44.0, BTS Spa, Milan, Italy) and processed using a custom protocol developed in SMARTanalyzer (Version 1.10.0469 BTS Spa, Milan, Italy).

3.7.1 Kinematics

Data were collected to calculate forearm position relative to the ground and elbow angular velocity using the IMU (BTS GSensor 2) attached to the wrist. The GSensor provides relative angles to the global coordinate system (GCS) about the north-east-up reference frame and angular velocity to the local coordinate reference (LCS) frame. Proprietary sensor fusion algorithms from the onboard IMU that generate these values have been previously investigated for validity and reliability for various motion analysis protocols (Kleiner et al., 2018; Kumar et al., 2023; Volkan et al., 2020). For this investigation, the data collection sample rate was 100 Hz, the acceleration range was set to a maximum of $\pm 2g$, and the gyroscope was set to $\pm 250^\circ/s$. Kinematic data were smoothed using a low-pass Butterworth filter with a cut-off frequency of 7 Hz as determined from the residual analysis results (Appendix D). Specifically, the cut-off frequency was determined by visually inspecting the curve generated by a custom MATLAB (version 9.13.0 R2022b, Mathworks Inc., Natick, Massachusetts, USA) code of the frequency versus the residuals of the sagittal angles to determine the point of deflection (Winter, 2009).

3.7.2 Event Detection

The sagittal plane angular velocity (y-axis of the GCS) of the arm curl movements was determined by taking the derivative of the sagittal plane angles of the forearm provided by the GSensor attached at the wrist. Each exercise trial was then trimmed to include only the relevant movement data from the sensor from the exercise movement. Next, the start of each of the concentric repetitions was determined when the angular velocity increased in the negative direction of the reference frame from zero and crossed a pre-established threshold of -10 deg/s. The concentric repetition ended when angular velocity decreased in the negative reference frame and crossed over the previously mentioned threshold. The start of the eccentric portion of the repetition was identified when the angular velocity exceeded the threshold of 10 deg/s, and the completion of the eccentric portion was determined when the angular velocity decreased back to 10 deg/s (Figure 4).

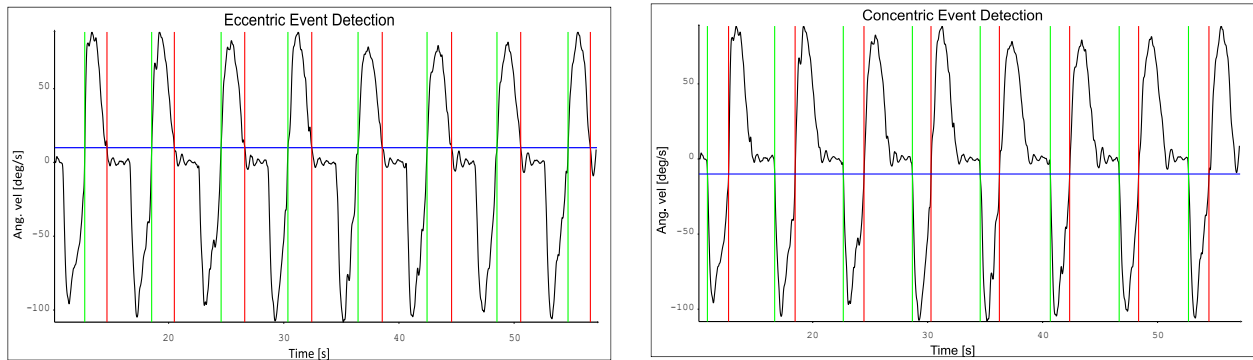


Figure 4. Concentric and eccentric start (green vertical line) and stop (red vertical line) as determined by crossing the predetermined reference threshold (blue horizontal line set at -10 deg/s concentric, $+10$ deg/s eccentric) for the dumbbell curl.

Verification of the start and end events of the exercise were confirmed by inspecting the video footage of the trial recorded by a video camera (BTS Vixta50, BTS Spa, Milan, Italy) synced with the IMU and surface EMG sensors. Inaccurate events (threshold crossings during the repetition or rest period, errors in movement during the repetition, and “false starts”) from the exercise trial were removed, and accurate events identifying the proper start and finish of the concentric and eccentric events were confirmed. The total number of events that were removed for each participant by trial and exercise can be seen in Table 5.

Table 5. Total number of events that were removed.

		Trial 1	Trial 2	Trial 3	Trial 4	Total
Participant 1	Concentration	4	0	0	0	4
	Dumbbell	0	0	0	1	1
	Hammer	4	0	6	0	10
	Incline	0	0	0	1	1
Participant 2	Concentration	0	0	16	22	38
	Dumbbell	2	2	4	0	8
	Hammer	0	0	0	0	0
	Incline	4	0	6	2	12
Participant 3	Concentration	10	8	2	14	34
	Dumbbell	30	2	9	12	53
	Hammer	9	1	4	16	30
	Incline	38	22	35	40	135
Participant 4	Concentration	2	10	13	6	31
	Dumbbell	2	8	18	8	36
	Hammer	4	6	2	2	14
	Incline	28	30	32	48	138
Participant 5	Concentration	6	2	0	4	12
	Dumbbell	4	2	6	2	14
	Hammer	4	8	4	0	16
	Incline	6	4	8	12	30
Participant 6	Concentration	0	0	0	0	0
	Dumbbell	0	2	0	0	2
	Hammer	0	0	0	0	0
	Incline	0	0	0	0	0
Participant 7	Concentration	12	10	16	10	48
	Dumbbell	10	24	14	16	64
	Hammer	6	2	12	11	31
	Incline	42	43	40	43	168
Participant 8	Concentration	12	12	8	6	38
	Dumbbell	2	4	0	4	10
	Hammer	10	6	6	10	32
	Incline	20	12	4	24	60
Participant 9	Concentration	18	0	12	0	30
	Dumbbell	0	0	0	0	0
	Hammer	0	0	0	2	2
	Incline	0	4	4	2	10
Participant 10	Concentration	6	1	2	8	17
	Dumbbell	0	2	4	2	8
	Hammer	4	0	2	1	7
	Incline	0	3	1	1	5
Participant 11	Concentration	26	0	4	0	30
	Dumbbell	0	4	0	0	4
	Hammer	0	0	6	0	6
	Incline	0	0	34	0	34
Participant 12	Concentration	0	2	0	0	2
	Dumbbell	0	0	0	0	0
	Hammer	0	0	0	0	0
	Incline	2	2	2	2	8
Participant 13	Concentration	4	10	18	4	36
	Dumbbell	2	4	0	0	6
	Hammer	4	0	2	0	6
	Incline	30	20	26	12	88
Participant 14	Concentration	8	6	0	0	14
	Dumbbell	6	4	4	0	14
	Hammer	4	2	4	8	18
	Incline	4	0	8	4	16
Participant 15	Concentration	2	0	0	4	6
	Dumbbell	0	0	1	0	1
	Hammer	2	0	3	2	7
	Incline	0	0	0	0	0

Removed events include threshold crossings during the repetition or rest periods, improper repetitions, and “false starts”. For each participant, 14 remaining events defined the 7 repetitions used to calculate SEMG amplitude from the last 4 repetitions of the trial.

3.7.3 SEMG Analysis

Raw SEMG signals (16-bit resolution sampled at 1000 Hz) were first bandpass filtered with a zero phase, fourth order Butterworth filter between 20 Hz and 450 Hz (Clancy et al., 2002). SEMG linear envelopes were then calculated and smoothed using the root mean square (RMS) with a 200 ms moving window (Soderberg & Knutson, 2000). The overall mean SEMG amplitude of the exercise was calculated by taking the average of the mean RMS values of the last four repetitions during the set.

For normalization purposes, two methods were chosen to reflect relative activation. Using the peak value of an MVIC is a standard method in SEMG studies examining muscle activation (Besomi et al., 2020; Burden, 2010). The peak RMS SEMG amplitude of the MVIC was determined by finding the maximum SEMG RMS amplitude value obtained during the three attempts at maximal activation of the target muscle. The second normalization method utilized the peak dynamic method (Bolgia & Uhl, 2007; Sousa et al., 2012), where the peak amplitude value obtained from the last four repetitions performed during the DBELL was used as the reference value for normalization. Normalizing values to the peak value instead of an overall mean or the mean value of several peaks represented a more straightforward interpretation and a better indication of relative activation between normalization methods for this study.

3.8 Statistical Analysis

Descriptive data for the four arm curls, including mean, standard deviation (SD), minimum (min) and maximum (max) values, range, consistency $ICC_{2,k}$, standard error of measurement (SEM), typical error (TE), coefficient of variation (CV), and minimum detectable change (MDC) were calculated in part using the psr package in R studio (Huebner et al., 2021). Individual consistency $ICC_{2,k}$ values were calculated in SPSS (version 29.0.1.0, IBM Corporation, USA).

A generalized linear mixed model (GLMM) was performed in R Statistical Software (v4.2.2; R Core Team 2022, Vienna, Australia) to examine the differences in normalized SEMG amplitude for the arm curl exercises, trial sessions, and the interaction between trial sessions and arm curl exercises. The glmmTMB package using a log link, which uses robust methods and optimal model selection, was chosen

as the preferred model to address data issues, including a positively skewed non-Gaussian distribution, and to incorporate both fixed and random effects to account for variability in individual responses to the arm curl exercises and over multiple trials (Brooks et al., 2017). Inspection of concentric and eccentric angular velocity data revealed a more Gaussian distribution with minimal deviation of residuals from predicted values. Therefore, a linear mixed model (LMM) from the package lme4 in R studio (Bates et al., 2015) was selected to examine the effect of exercise, trial and the interaction between trials and exercise.

Various mixed models were examined with different combinations of factors, and the following models were chosen due to the favourable Akaike information criteria (AIC) score:

$$\text{GLMM} \leftarrow \text{glmmTMB}(\text{NormEMG} \sim \text{Exercise} + \text{Trial} + \text{Exercise:Trial} + (1|\text{Participant/Trial}))$$
$$\text{LMM} \leftarrow \text{lme4}(\text{Angular Velocity} \sim \text{Exercise} + \text{Trial} + \text{Exercise:Trial} + (1|\text{Participant/Trial}))$$

The MVIC normalized (MVCnorm) and dynamic peak normalized (DYNnorm) SEMG amplitudes for the CONC, DBELL, HAMM, and INCL were identified as the dependent variables for the GLMM. Both normalized values are expressed as a ratio of the mean SEMG amplitude of the exercise's last four repetitions divided by the normalization method's peak value. Angular velocity was defined as the dependent variable for the LMM in degrees per second, where concentric angular velocity was negative and eccentric velocity was positive. Both models included a random intercept for each trial nested within each participant to represent a smaller sample of a larger population of individuals and training sessions. Fixed effects were the performed exercises, the trials, and the interaction between the exercises and the trials. Interactions were considered significant if p-values were less than the critical alpha value of 0.05 ($p < 0.05$). If significance was found between the fixed factors and the interaction, a post hoc analysis using a multiple comparison approach with a Tukey's correction factor was performed to identify where the differences occurred.

Absolute intraclass correlation coefficients (ICC) were calculated from the GLMM for each exercise separately to determine variability across the four trial sessions. ICC values were classified as follows: poor (< 0.4), weak ($0.4 - 0.54$), moderate ($0.55 - 0.69$), good ($0.7 - 0.84$), and excellent (≥ 0.85) (Schober et al., 2021). Measures of standardized differences between estimated marginal means to approximate the equivalent of Cohen's d effect size in mixed models (Mattan et al., 2020) for contrasts between exercises and trials were calculated by using the emmeans package (Lenth et al., 2024). In addition, to determine the influence of the fixed effects of the exercises over the multiple trials on SEMG amplitude, unadjusted (or conditional) ICC values were subtracted from adjusted ICC values as suggested by Nakagawa et al. (2017) and described by Alhammound et al. (2022).

For effect size, values between 0 and 0.10 were interpreted as a trivial effect, 0.10 to 0.34 as small, 0.35 to 0.64 as medium, 0.65 to 1.19 as large, and values of greater than 1.20 as very large (Schober et al., 2021). A Pearson correlation was performed to test the relationship between the change in contrast effect sizes between the four exercises over different trials. A correlation of ≥ 0.9 indicates a very strong correlation, $0.7 - 0.89$ a strong correlation, $0.4 - 0.69$ a moderate correlation, and ≤ 0.39 a weak correlation (Schober et al., 2021). For example, a very strong correlation would indicate that the effect size (the magnitude of the SEMG amplitudes) between the exercises did not change substantially over the trials and, therefore, could be interpreted as the relationship between exercises being stable over the trials.

CHAPTER 4: RESULTS

4.1 Descriptive Data

Raincloud plots, combining a density plot, a box and whisker plot, and individual data values for each exercise over the four trials, are provided in Figures 5 and 6 to visualize the normalized SEMG values for each exercise.

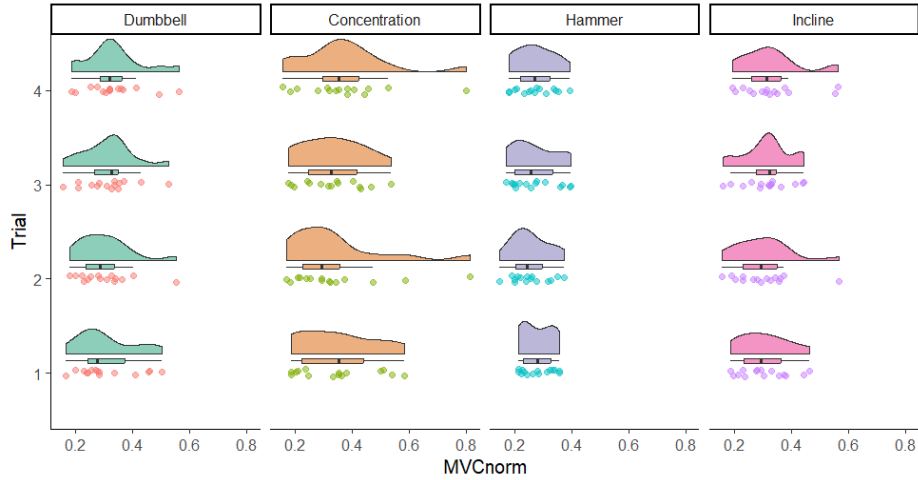


Figure 5. Raincloud plots of each exercise and respective trial for SEMG normalized to MVIC. Density plots represent the data distribution. Box and whisker plots show the median, quartile range, and minimum and maximum values not including outliers. Dots represent individual data points.

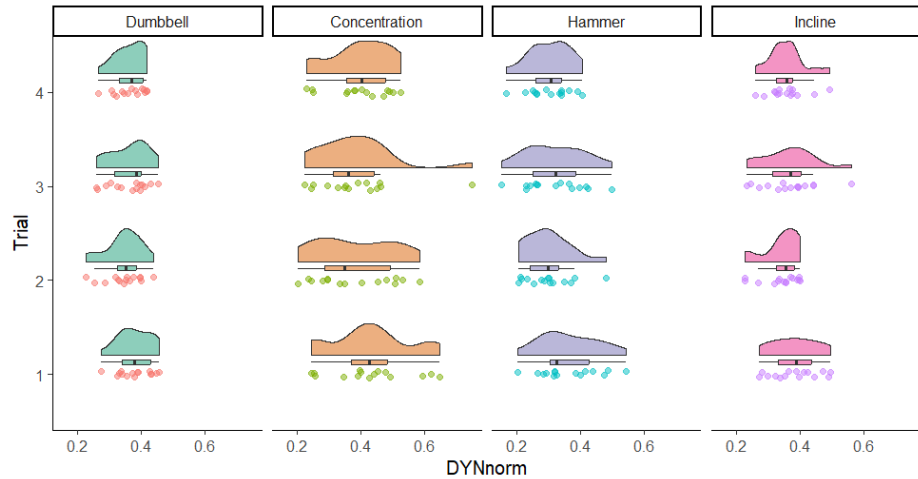


Figure 6. Raincloud plots of each exercise and the respective trial for SEMG normalized to the dynamic peak. Density plots represent the data distribution. Box and whisker plots show the median, quartile range, and minimum and maximum values not including outliers. Dots represent individual data points.

Data describing muscle soreness and overall fatigue for participants are presented in Table 6.

Mean soreness level was reported as having very little pain, and fatigue level was reported as having slight fatigue levels on average for each trial.

Table 6. Participant descriptive data for soreness and fatigue

Participant	n	Day 1		Day 2		Day 3		Day 4	
		Soreness Mean (SD)	Fatigue Mean (SD)	Soreness Mean (SD)	Fatigue Mean (SD)	Soreness Mean (SD)	Fatigue Mean (SD)	Soreness Mean (SD)	Fatigue Mean (SD)
Female (Trained)	3	6.9 (9.7)	22.2 (15.1)	6.7 (9.8)	16.6 (15.1)	4.1 (4.5)	14.4 (13.7)	10.4 (16.6)	31.9 (27.3)
Female (Untrained)	3	9.7 (0.3)	30.7(19.9)	18.3 (4.7)	28.7 (16.6)	18.2 (4.8)	31.5(16)	12.1 (7)	19.2 (18.2)
Male (Trained)	5	5.6 (9.5)	16.1 (21.4)	4.9 (6)	13.7 (15.9)	8.2 (16.4)	12.1 (15.7)	3.1 (4.9)	26.7 (33.5)
Male (Untrained)	4	3.6 (4.1)	16.8 (16)	1.4 (1.7)	28.2 (40)	3.2 (2.6)	34.5 (21.2)	2.4 (1.9)	15.5 (19.5)
All	15	6.1 (6.9)	20.4 (17.3)	7 (8.1)	21.2 (23.4)	8 (10.8)	22.4 (18.5)	6.2 (8.6)	23.3 (24.5)

Scale range is from 0 – 100 for both soreness and fatigue where 0 represents no soreness or fatigue and 100 representing unbearable soreness or fatigue. SD = standard deviation. Units are a decimal fraction (ratio) of the marked line from the start of the scale /length of the scale.

Table 7 presents summary descriptive data for the four arm curls, including mean, standard deviation (SD), minimum (min) and maximum (max) values, range, consistency $ICC_{2,k}$, standard error of measurement (SEM), typical error (TE), coefficient of variation (CV), and minimum detectable change (MDC) across the four trials.

Table 7. Descriptive data of exercises for MVCnorm and DYNnorm

Exercise (MVCnorm)	Mean (SD)	Min – max (range)	$ICC_{2,k}$	SEM	TE	CV	MDC
Concentration Curl	0.35 (0.14)	0.16-0.81 (0.66)	0.93	0.038	0.069	20	0.104
Dumbbell Curl	0.32 (0.1)	0.16-0.56 (0.41)	0.86	0.035	0.061	19.4	0.099
Hammer Curl	0.27 (0.07)	0.15-0.40 (0.25)	0.81	0.028	0.046	17.2	0.079
Incline Curl	0.31 (0.09)	0.16-0.57 (0.41)	0.90	0.03	0.053	17	0.082
Exercise (DYNnorm)	Mean (SD)	Min – max (range)	$ICC_{2,k}$	SEM	TE	CV	MDC
Concentration Curl	0.40 (0.12)	0.20-0.75 (0.54)	0.83	0.048	0.079	19.9	0.163
Dumbbell Curl	0.36 (0.05)	0.22-0.46 (0.23)	0.75	0.027	0.041	11.3	0.132
Hammer Curl	0.32 (0.08)	0.15-0.54 (0.39)	0.69	0.047	0.065	20.2	0.101
Incline Curl	0.36 (0.07)	0.23-0.56 (0.33)	0.59	0.045	0.06	16.5	0.166

SD = standard deviation. SEM = standard error of measurement. TE = typical error. CV = coefficient of variation. MDC = minimal detectable change. $ICC_{2,k}$ = consistency intraclass correlation coefficient. Units are a decimal fraction (ratio) of the SEMG amplitude/normalized value.

Consistency measures of ICC_{2,k} assesses the degree of similarity between the specific exercise SEMG amplitudes for that individual. TE is an absolute measurement that describes the variance due to non-related factors, and although SEM is similar, it incorporates the ICC_{2,k} values to explain the variance around the mean; CV is the relative proportion of the TE as a percentage of the mean, and MDC quantifies the measurement using a 95% confidence interval that the difference in values was not due to chance (McGinn et al., 2021). Table 8 lists individual demographics for training status, sex, and consistency ICC_{2,k} measures for all exercises.

Table 8. Individual consistency ICC_{2,k} values

Participant Demographics			MVCnorm Reliability			DYNnorm Reliability		
ID	Training Status	Sex	ICC _(MVC)	95% CI	p	ICC _(DYN)	95% CI	p
1	T	M	0.952	[0.755, 0.997]	<.001	0.939	[0.728, 0.996]	<.001
2	T	F	<u>0.129</u>	[-3.425, 0.94]	.382	<u>-0.06*</u>	[-0.829, 0.867]	.481
3	T	F	0.941	[0.7, 0.996]	<.001	0.791	[0.223, 0.984]	.002
4	U	F	0.894	[0.464, 0.993]	.004	0.842	[0.287, 0.989]	.014
5	U	F	0.988	[0.937, 0.99]	<.001	0.865	[0.309, 0.99]	<.001
6	T	M	0.977	[0.885, 0.998]	<.001	0.878	[0.382, 0.997]	<.001
7	T	M	<u>-0.392*</u>	[-6.07, 0.904]	.566	<u>-0.166*</u>	[-0.572, 0.768]	.613
8	U	M	<u>-0.369*</u>	[-5.953, 0.905]	.559	<u>0.039</u>	[-0.216, 0.79]	.373
9	U	F	0.964	[0.815, 0.997]	<.001	0.805	[0.233, 0.985]	<.001
10	T	M	0.953	[0.761, 0.997]	<.001	0.875	[0.417, 0.991]	<.001
11	T	M	0.85	[0.239, 0.99]	.011	<u>0.362</u>	[-0.02, 0.908]	.012
12	U	M	0.956	[0.776, 0.997]	<.001	0.949	[0.766, 0.996]	<.001
13	T	F	0.658	[-0.737, 0.976]	.093	<u>0.054</u>	[-0.012, 0.541]	.067
14	U	M	<u>0.17</u>	[-3.214, 0.943]	.362	<u>0.165</u>	[-1.297, 0.929]	.346
15	U	M	0.799	[-0.021, 0.986]	.026	0.7	[0.011, 0.977]	.028

ICC ratings are identified as **excellent**, **good**, moderate, *weak*, and poor. * = negative ICC values indicate within exercise variance was greater than between exercise variances. CI = Confidence Interval.

4.2 Effect of Exercise and Trial on Angular Velocity

There were significant main effects for both concentric ($\chi^2(3, N = 60) = 132.95, p < .001$) and eccentric ($\chi^2(3, N = 60) = 83.94, p < .001$) angular velocity across the exercises. Significant main effects were also seen for the trials for both concentric ($\chi^2(3, N = 60) = 8.03, p < .045$) and eccentric ($\chi^2(3, N = 60) = 20.38, p < .001$) angular velocity. Post hoc tests using Tukey's correction factor revealed that concentric angular velocity was higher for HAMM ($p = .002, ES = 0.636$ or large) and INCL ($p < .001, ES = 1.067$ or large) than CONC. INCL was found to have a significantly higher concentric angular

velocity than DBELL ($p = .02$, $ES = 0.392$ or medium). Eccentric angular velocity was found to be lower in CONC ($p < .037$, $ES = 0.534 - 0.926$ or medium to large) than in all other exercises.

Although the ANOVA showed a main effect of the trial on concentric angular velocity, post hoc analyses using Tukey's correction factor revealed no significant differences between trials ($p > 0.28$). Eccentric angular velocity was higher during trial 4 than in trials 1 ($p = 0.008$, $ES = 0.515$ or medium) and 2 ($p = 0.048$, $ES = 0.053$ or trivial). No significant interactions were found between both angular velocities and the interaction between exercise and trial ($p = 0.457$).

4.3 Effect of Exercise and Trial on SEMG Amplitude

Figures 7 and 8 illustrate the estimated means along with individual data points of MVCnorm and DYNnorm, respectively.

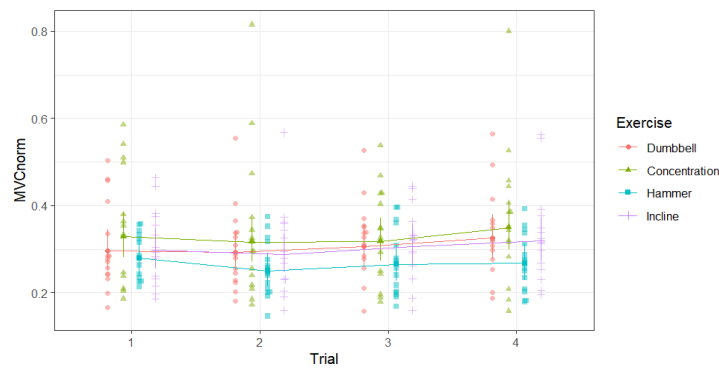


Figure 7. Individual data points for each exercise normalized to an MVIC along with estimated marginal means over four trials for each exercise.

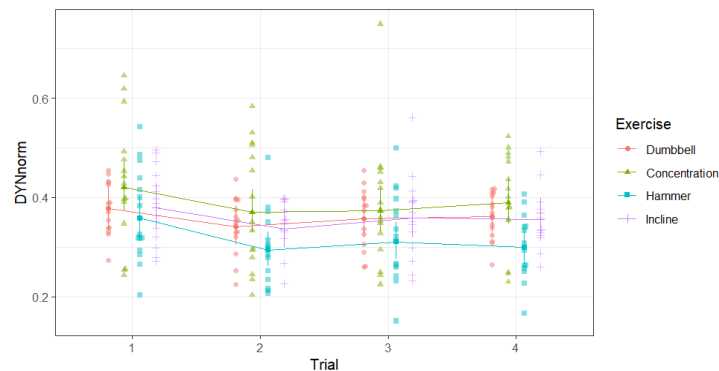


Figure 8. Individual data points for each exercise normalized to the dynamic peak along with estimated marginal means over four trials for each exercise.

There was a significant main effect for both MVCnorm ($\chi^2(3, N = 60) = 8.35, p = .039$) and DYNnorm ($\chi^2(3, N = 60) = 7.88, p = .049$) for the arm curl exercises. Post hoc tests using Tukey's correction factor and effect size indicated that CONC curl was significantly higher than HAMM for MVCnorm ($p = .023, ES = 0.694$ or large) and DYNnorm ($p = .031, ES = 0.909$ or large). Overall effect sizes for exercise contrasts and correlations between trials for MVCnorm and DYNnorm are shown in Tables 9 and 10, respectively. Effect sizes across trials between INCL and DBELL were trivial, medium to large between CONC and HAMM curl, and small to medium for the remaining comparisons.

Table 9. Relational effect size contrasts for MVCnorm

Trial 1	MVCnorm Effect Size Contrast				Pearson Correlation Between Trials (95% CI)			
	Concentration	Dumbbell	Hammer	Incline	Trial 1x1	Trial 1x2	Trial 1x3	Trial 1x4
Concentration	0	0.341	0.534	0.327				
Dumbbell	-0.341	0	0.193	-0.014		0.928	0.848	0.899
Hammer	-0.534	-0.193	0	-0.207	1	(0.757-0.980)	(0.534-0.956)	(0.672-0.972)
Incline	-0.327	0.014	0.207	0				
Trial 2					Trial 2x1	Trial 2x2	Trial 2x3	Trial 2x4
Concentration	0	0.249	0.771	0.308				
Dumbbell	-0.249	0	0.521	0.058	0.928		0.98	0.997
Hammer	-0.771	-0.521	0	-0.463	(0.757-0.980)	1	(0.927-0.994)	(0.990-0.999)
Incline	-0.308	-0.058	0.463	0				
Trial 3					Trial 3x1	Trial 3x2	Trial 3x3	Trial 3x4
Concentration	0	0.128	0.595	0.129				
Dumbbell	-0.128	0	0.468	0.001	0.848	0.98		0.991
Hammer	-0.595	-0.468	0	-0.466	(0.534-0.956)	(0.927-0.994)	1	(0.968-0.998)
Incline	-0.129	-0.001	0.466	0				
Trial 4					Trial 4x1	Trial 4x2	Trial 4x3	Trial 4x4
Concentration	0	0.237	0.876	0.299				
Dumbbell	-0.237	0	0.639	0.062	0.899	0.997	0.991	
Hammer	-0.876	-0.639	0	-0.577	(0.672-0.972)	(0.990-0.999)	(0.968-0.998)	1
Incline	-0.299	-0.062	0.577	0				

Contrasts indicate comparison of effect size between arm curl exercises for MVCnorm. Correlations indicate the strength of the relationship between the effect sizes over corresponding trials.

Pearson correlations between trials were strong to very strong for both MVCnorm ($r(10) = 0.848-0.997, p < .001$), and DYNnorm, ($r(10) = 0.833-0.996, p < .001$), indicating that the magnitude of the difference between exercises remained throughout the trials. If a learning effect occurred after the first

trial, eliminating the first trial correlation values resulted in correlation values > 0.976 (0.976–0.997) or very strong. Analysis of the effect of the trial on MVCnorm and DYNnorm showed no significant main effect of the trial. There was no significant exercise:trial interaction effect for SEMG amplitude for both normalization methods.

Table 10. Relational effect size contrasts for DYNnorm

DYNnorm Effect Size Contrast					Pearson Correlation Between Trials (95% CI)			
Trial 1	Concentration	Dumbbell	Hammer	Incline	Trial 1x1	Trial 1x2	Trial 1x3	Trial 1x4
Concentration	0	0.468	0.690	0.436	1	0.922 (0.74-0.978)	0.833 (0.497-0.952)	0.884 (0.629-0.967)
Dbell	-0.468	0	0.222	-0.032				
Hammer	-0.690	-0.222	0	-0.254				
Incline	-0.436	0.032	0.254	0				
Trial 2	Concentration	Dumbbell	Hammer	Incline	Trial 2x1	Trial 2x2	Trial 2x3	Trial 2x4
Concentration	0	0.348	0.999	0.414	0.922 (0.74-0.978)	1	0.976 (0.915-0.994)	0.996 (0.985-0.999)
Dbell	-0.348	0	0.651	0.066				
Hammer	-0.999	-0.651	0	-0.584				
Incline	-0.414	-0.066	0.584	0				
Trial 3	Concentration	Dumbbell	Hammer	Incline	Trial 3x1	Trial 3x2	Trial 3x3	Trial 3x4
Concentration	0	0.187	0.800	0.175	0.833 (0.497-0.952)	0.976 (0.915-0.994)	1	0.99 (0.965-0.997)
Dbell	-0.187	0	0.613	-0.012				
Hammer	-0.800	-0.613	0	-0.625				
Incline	-0.175	0.012	0.625	0				
Trial 4	Concentration	Dumbbell	Hammer	Incline	Trial 4x1	Trial 4x2	Trial 4x3	Trial 4x4
Concentration	0	0.319	1.146	0.401	0.884 (0.629-0.967)	0.996 (0.985-0.999)	0.99 (0.965-0.997)	1
Dbell	-0.319	0	0.828	0.082				
Hammer	-1.146	-0.828	0	-0.745				
Incline	-0.401	-0.082	0.745	0				

Contrasts indicate comparison of effect size between arm curl exercises for DYNnorm. Correlations indicate the strength of the relationship between the effect sizes over corresponding trials.

4.4 Reliability and Repeatability of SEMG over Trials

Reliability and repeatability measurements are shown in Table 11. The arm curl exercises accounted for a small proportion of the variance in MVCnorm and DYNnorm (5.8% and 9.1%, respectively). The trials contributed even less to the variance observed in SEMG amplitudes. In the full model, the interaction of exercise:trial resulted in a slightly higher contribution to the variances. The random effects of the participants and trials (R^2 conditional – R^2 marginal) contributed the most to the

variance in both normalization methods. DYNnorm had approximately 15% higher residual variance than MVCnorm.

Table 11. Reliability and repeatability

Variance	MVCnorm		DYNnorm	
	R ²	95% CI	R ²	95% CI
Exercise: Trial				
<i>R² Conditional</i>	0.757	[0.628, 0.858]	0.594	[0.628, 0.717]
<i>R² Marginal</i>	0.073	[0.036, 0.212]	0.14	[0.085, 0.271]
Exercise				
<i>R² Conditional</i>	0.751	[0.57, 0.868]	0.584	[0.439, 0.704]
<i>R² Marginal</i>	0.058	[0.016, 0.125]	0.091	[0.04, 0.18]
Trial				
<i>R² Conditional</i>	0.465	[0.256, 0.596]	0.684	[0.375, 0.807]
<i>R² Marginal</i>	0.039	[0.002, 0.260]	0.011	[0.001, 0.076]
Reliability	ICC	95% CI	ICC	95% CI
<i>ICC adjusted</i>	0.738	[0.553, 0.877]	0.528	[0.303, 0.676]
<i>ICC unadjusted</i>	0.684	[0.460, 0.844]	0.454	[0.243, 0.583]
<i>ICC fixed</i>	0.054		0.074	
ICC by group				
<i>Participant</i>	0.597		0.311	
<i>Participant: Trial</i>	0.141		0.217	
ICCMixed				
<i>Concentration</i>	0.818		0.588	
<i>Dumbbell</i>	0.654		0.42	
<i>Hammer</i>	0.546		0.392	
<i>Incline</i>	0.751		0.251	
Repeatability	R(SE)	95% CI	R(SE)	95% CI
Participant	0.543(0.117)*	[0.282, 0.714]	0.217(0.086)*	[0.047, 0.42]
Residual	0.302(0.08)	[0.19, 0.484]	0.519(0.075)	[0.388, 0.689]
Fixed	0.083(0.038)	[0.06, 0.204]	0.151(0.059)	[0.123, 0.343]

*ICCfixed (ICC adjusted – ICC unadjusted) is an alternative to calculate the effect of the fixed effects (trial and exercise) on SEMG amplitude. R² conditional represents the variance explained by the model including both fixed and random effects. R² marginal represents the variance explained by only the fixed effects. ICCmixed represents the absolute ICC calculated from the GLMM. * = p < .001*

Adjusted ICC values with parametric bootstrapping of 100 samples for MVCnorm and DYNnorm indicated moderate reliability. The effect size of the fixed effects of exercise, trial and exercise:trial on the reliability of MVCnorm and DYNnorm was trivial (adjusted ICC - unadjusted ICC), and it is suggested that these fixed factors have a negligible effect on SEMG amplitude and reliability. At the group level, considering the contribution of random effects to obtaining reliable measurements for MVCnorm, the participants explained nearly 60% of the variation in values instead of the minor

contribution of the trials. DYNnorm reliability suggested higher residual variance from other factors, as ICC values associated with the participants explained approximately 30% of the variance, while the trial contribution was slightly over 20%.

Repeatability calculated for within-participant variation considering the interaction of exercise:trial with parametric bootstrapping of 100 samples for MVCnorm and DYNnorm suggests that the model prediction values for MVCnorm are more repeatable for participants over trials than DYNnorm. The model to calculate repeatability using rptR (Stoffel et al., 2017) in RStudio was fitted with a Gaussian log distribution, where slight deviations were detected in the residuals of the first quantile for MVCnorm. Therefore, it should be interpreted with caution.

Absolute ICC results calculated from the GLMM (ICCmodel) for each exercise separately ranged from moderate to good agreement (MVCnorm ICCmodel = 0.546–0.818) for MVCnorm. DYNnorm resulted in lower ICC values, ranging from poor to moderate agreement (DYNnorm ICCmodel = 0.251–0.588). ICCmodel uses the glmmTMB model to depict ICC values, where values close to 1 indicate the same SEMG amplitudes for individuals across all trials, but with different absolute values between participants. ICCmodel values close to 0 suggest that absolute values between participants are the same and that all the variance of the SEMG amplitude for that exercise is within the individual. ICCmodel values close to 0.5 indicate equal variance between the individual across trials and that participants have different absolute values from others (Wiley, 2024).

CHAPTER 5: DISCUSSION

The main finding of this study is that the exercise ranking determined on the first session maintains the same relationship across the four trials. In a practical sense, this study aimed to provide practicing clinicians who prescribe resistance training exercises based on SEMG amplitude information regarding whether the prescribed exercise would maintain the initial ranking over other exercises and multiple training sessions. Contrast effect sizes between the arm curl exercises were determined and were then correlated between trials to answer this question. When all trials were included, correlations were strong (> 0.835). Correlation values increased and were very strong when the first trial was excluded (> 0.982). Slightly lower correlations for comparisons during trial one over the others may indicate a learning effect in how the exercises were initially performed. These high correlation values show that the magnitudes between the exercises for both MVCnorm and DYNnorm stayed similar even though absolute SEMG amplitudes for each exercise may have varied proportionally on different days, thus maintaining their rank over the other exercises. This consistent relationship between exercise rank over multiple training sessions would suggest that practitioners and researchers can be confident that the exercise selected based on normalized SEMG rank will maintain its position over a training macrocycle.

Although absolute SEMG amplitude varied substantially in response to exercise selection between individuals and a small amount between trials, the relationship between the exercises for the biceps brachii and SEMG amplitude remained strong to very strong. The data suggest that normalizing SEMG amplitude values to an MVIC is more reliable than normalizing to the peak value of a dynamic movement when considering absolute values. However, both methods maintain the SEMG amplitude relationship between exercises over multiple trials. In addition, the model suggests that HAMM showed weak agreement compared to moderate to good agreement for the remaining exercises. There were no significant trial or exercise:trial differences between SEMG normalization methods.

The CONC was significantly higher than HAMM but not significantly different than INCL or DBELL. This similarity in SEMG amplitudes is also comparable to Oliveira et al. (2009), where they

found no significant differences in SEMG amplitudes between the DBELL and the INCL. In addition, another study also found that CONC SEMG amplitude was significantly higher than a standard supinated grip dumbbell curl, possibly due to the lack of involvement of the supporting muscle action of the anterior deltoid (Bagchi & Raizada, 2019). This explanation may be why the CONC resulted in higher SEMG amplitude in comparison to the other exercises in this study. Although instructions to perform the exercise movements properly were given to the participants, other factors, such as voluntarily engaging in co-contraction or “flexing” the muscle while performing the exercise, particularly in the trained participants, may have resulted in increased SEMG amplitude as well (Maeo et al., 2013; Paoli et al., 2019).

The HAMM consistently had a lower MVCnorm SEMG amplitude than the other three exercises. This relative SEMG amplitude also agrees with other studies investigating biceps brachii excitation between supinated and neutral hand grips (Buchanan et al., 1989; Coratella et al., 2023). Higher biceps excitation in a supinated grip versus a neutral grip may be explained by higher displacement in the muscle-tendon junction (Lau et al., 2021) and a necessary higher activation to generate adequate force at a shorter muscle length in combination with individual muscle synergies (Buchanan et al., 1989). In contrast to these findings, Kleiber et al. (2015) found no statistical differences in biceps brachii excitation between supinated and neutral grips. However, this last study only examined unweighted arm flexion and did not investigate biceps brachii SEMG during dynamic resistance exercise. Kohn et al. (2018) also found no significant differences in biceps excitation in neutral and supinated grips. Nevertheless, this study only investigated maximal isometric contractions and may not be comparable to isotonic movements such as those used in this study.

Significant differences in angular velocity between the CONC and HAMM and the INCL and HAMM were found. The CONC was performed slower than HAMM, while the INCL curl was performed faster than the HAMM. This difference is likely due to the presumed shorter displacement the dumbbell needs to travel in two seconds for each repetition portion, although displacement was not

directly measured. The exercise with the highest SEMG amplitude had significantly lower angular velocities when compared to the other exercises, which is somewhat contrary to what has been previously reported in other studies on SEMG amplitude and velocity on the trunk (Fan et al., 2014) and arm flexors (Potvin, 1997; Sy & Bugtai, 2014; von Werder & Disselhorst-Klug, 2016). These studies examined the same movement over different velocities as opposed to different movements over similar velocities that this study implemented. This finding may support the notion that specific movements may cause differences in SEMG amplitude when execution speed is similar. However, when angular velocity measures were added to the model, the explained variance of normalized SEMG amplitude increased by only an additional 1 to 2%, as indicated by the R-squared values. Due to this trivial effect on SEMG amplitude, it is unlikely to have had a significant impact.

The overall reliability of SEMG amplitude of MVCnorm was in the higher range of moderate (ICC = 0.738). This coefficient value is slightly lower than that found in other studies that examined muscle excitation in the biceps brachii during dynamic contractions (Stock et al., 2010). DYNnorm reliability (ICC = 0.528) was at the low end of the moderate range and considered less repeatable than MVCnorm. Differences in reliability and repeatability have been found between MVIC and dynamic normalization methods (Bolgla & Uhl, 2007) and this was also found in this study, where there was an approximate difference of 30% in variance between the two methods. A single peak value from multiple isometric maximal contractions has been found to have better reliability than the mean of several MVICs (Gaudet et al., 2016); however, compared to dynamic normalization methods, the average obtained from several dynamic peak measurements is considered more reliable than a single measurement (Burden, 2010). This difference in normalization methods could explain the lower reliability for the DYNnorm values, as only a single peak value was used to normalize SEMG values from the DBELL. As the only difference between MVCnorm and DYNnorm was the value used for normalization, using the mean of several peak values from the DBELL for DYNnorm may have improved reliability when compared to the MVCnorm. In addition, fluctuations in day-to-day SEMG amplitudes during the DBELL, which was

found to have moderate reliability when normalized to an MVIC, would have affected the normalized absolute values in addition to the inter- and intra-individual variations observed.

ICC values calculated from the variances obtained from the GLMM examined the reliability of each exercise. They showed CONC as the most reliable, followed by INCL, DBELL and HAMM for MVCnorm. Due to the trivial, fixed effect size of the exercises and the trials for both normalization methods (ES calculated from ICC of 0.054 – 0.074) on SEMG amplitude and the corresponding large amount of variance explained by the participants (>68% and >45% for MVCnorm and DYNnorm respectively) it is clear there is high heterogeneity across participants, and this may have contributed to the reliability of the exercises. Rainoldi et al. (1999) also found diverse individual reliability measures when examining the biceps brachii during isometric contractions at increasing intensities. Average rectified values (ARV) of the SEMG signal produced by the biceps brachii resulted in poor ICC values and inconsistent slopes for ARV rate of change. In addition, unlike the repeated measures ANOVA used in some of the previously mentioned studies, the GLMM used in this investigation may be more applicable for assessing the suitability of SEMG over repeated measures for exercise prescription. This is because GLMMs consider not only the effects of the exercise and training sessions, even in non-normal distributions, but also the random effects of between- and within-individual variations in hierarchical data (Hayat & Hedlin, 2012). This difference in statistical approach may also have contributed to the findings when compared to other studies that did not use this approach.

The high participant variability may be due to unique individual muscle recruitment patterns. Muscle synergies, including for the biceps brachii, have been found to have moderate reliability depending on the task and the individual (Kristiansen et al., 2016; Taborri, Palermo, et al., 2018). Specifically, activation of the biceps brachii during arm flexion can show significant inter-individual differences and is most likely due to muscle morphological differences expressed during changes in joint angle and moment as well as different recruitment strategies of other muscles to optimize load-sharing efficiency (Praagman et al., 2008, 2010). As for how this affects exercise prescription, in certain cases it

may be advisable to evaluate muscle activation individually to more accurately predict the necessary training adaptations.

Interestingly, descriptive individual ICCs calculated for each participant to help describe the SEMG amplitude reliability of each exercise over the four trials supported this finding. Just over 65% of MVCnorm and approximately 50% of DYNnorm ICC_{2,k} consistency values were good to excellent. Most of the remaining values were described as poor, and in some cases, negative values, regardless of training status. Although negative ICC values may be theoretically impossible in populations (Giraudeau, 1996), the small sample size involving the individual application in this specific case could result in negative values and may be interpreted as total disagreement (Costa-Santos et al., 2011; Eldridge et al., 2009). In practical terms, this can happen when the within-individual exercise variance exceeds the between-individual variance (Rainoldi et al., 1999; Shieh, 2016). This bimodal distribution suggests that individuals are either very consistent in their SEMG amplitudes for each exercise or not at all consistent for the exercises performed. Although the reason for this is unclear, it does not appear to be related to training status. Pre-existing or genetic predispositions in corticospinal efficiencies and muscle synergy patterns may have played a role (Cheung et al., 2024; Hutchinson et al., 2018). Additionally, some participants were directly related (parent/child or sibling relationship), which may have influenced the distribution of reliability values across participants. This type of bimodal distribution in ICC values may also have affected the calculations of overall values, and further research into this individual response may help explain the significant differences.

Lower reliability scores may also be due to variations in exercise execution over the trials. Although no main and post hoc significant interactions were found for concentric angular velocity between trials or the interaction between exercises and trials, there was a difference in eccentric velocity between trial four and the first and second trials. Slight differences in supination, pronation, and shoulder flexion may also have occurred that were not visually identifiable during the performance of the exercise, which may have had a role in muscle excitation. In addition, the mean angular velocity does not provide

insight into the timing of the angular acceleration profiles. For example, a higher initial angular acceleration may have resulted in a different SEMG profile than a mid-repetition acceleration increase or a faster deceleration at the end of the movement. Examining these profiles in combination with angular jerk, defined as the third derivative of the angle or the rate of change of angular acceleration (Eager et al., 2016), may be an additional variable to investigate the effect of smoothness of movement on SEMG reliability.

There is a need for more literature that investigates the reliability and repeatability of the relationship between resistance training exercises. Focus is typically on the normalized amplitude, and comparisons are then drawn from the relationship of that amplitude to other exercises that target the same muscle or groups of muscles for an appropriate training adaptation. There is indirect evidence to support this inference method as a higher SEMG amplitude may infer a more significant stimulus to the motor units and, consequently, greater tension and workload performed by the muscle fibres within that motor unit (Ema et al., 2013; Spiliopoulou et al., 2022; Zabaleta-Korta et al., 2021). However, inter- and intra-individual variation exists in absolute normalized SEMG amplitudes depending on numerous factors and, therefore, may not be practical to use when selecting a single exercise for long-term rehabilitation, performance, or aesthetic reasons. Neural adaptations occur rapidly in the first few weeks and plateau over time (Carroll et al., 2001; Folland & Williams, 2007). This fluctuation in muscle excitation patterns may affect muscle synergy patterns, ultimately affecting the stimulus on the target muscle. However, in a practical sense, the relationship between exercises that target a specific muscle for adaptation often allows the clinician to select the best exercise from a group of exercises to achieve the desired goal for the individual. Although normalizing to an MVIC is more reliable than using a single peak value from a reference movement to normalize the signal, this first method has less practicality when used in the field due to the increased time and effort to perform the MVIC for the involved muscle. Normalizing to a dynamic movement reduces data collection time, and improved reliability may be obtained by taking an average of multiple peaks or mean values for each repetition. Regardless of the normalization process, the

relationship between exercises over the trials shows a high correlation and appears to hold over multiple sessions. This approach of exercise selection would be the preferred method to rate exercise effectiveness comparatively rather than estimating muscle excitation as a percentage of a reference value. Although normalizing the SEMG signal to an MVC may be more reliable for SEMG amplitude values, the dynamic peak method to normalize the signal may have greater ecological validity in practice as this method is less time intensive, uses existing data, and has similar results on the stability of the ranking of the exercise over time.

There are several limitations to this study. As this examination only assessed reliability for exercises that affect the biceps brachii, different muscle groups with different structural characteristics, such as muscle fibre pennation angle, innervation zone location, and location of the musculotendon junction, may alter reliability (Enoka & Duchateau, 2016; Kamen & Caldwell, 1996; Rainoldi et al., 2000). In addition, a different intensity of contraction may also affect reliability. Participants were asked to perform the exercises at approximately one third of MVIC, equating to a maximum of 15 – 20 repetitions in practice. This intensity was chosen to decrease the risk of injury and muscle soreness and to ensure proper exercise execution. However, higher intensities may also decrease (Kellis & Katis, 2008) or increase (Rainoldi et al., 1999) reliability.

The exercises were also performed at a controlled pace of two seconds for both the full concentric and eccentric contraction to minimize the effect of velocity on the SEMG amplitude. However, such restrictions in movement may alter the individual recruitment strategies and affect the SEMG amplitude (Crouzier et al., 2019) over the trials. Although angular velocity was controlled by having the participants synchronize the elbow flexion to a metronome, angular acceleration was not controlled. Therefore, it is conceivable that different participants could have had different acceleration profiles and consequently generated forces at different rates, thus affecting the recruitment of motor units.

Only four exercises were chosen to be examined. Different exercises may have different reliability due to differences in muscle synergies and joint moment forces. In addition, this study

examined only 15 participants from diverse training backgrounds and age demographics. A larger, more targeted population may have generated different results. Finally, some reliability statistics could not be calculated using the glmmTMB model to accommodate the skewed data observed for many of the exercises for both normalized methods. Therefore, some repeatability and reliability statistics should be interpreted cautiously.

CHAPTER 6: CONCLUSION

Although the absolute SEMG amplitudes for the biceps brachii may vary across different training sessions, they demonstrate moderate to good reliability when considering the random effects for the participant and trial. The exercise ranking based on both normalized SEMG amplitude methods remains consistent, and that relationship strongly correlates with the other trials. Using the peak value from MVICs to normalize the signal is more reliable than using the single peak of a similar dynamic movement. However, the reliability of the latter method may be improved by taking the average of multiple peaks. Using a dynamic movement to normalize may also have greater ecological validity as it requires less time and effort from the participant than obtaining multiple valid MVICs. Researchers and clinicians can be confident that the rank order assigned to a resistance training exercise for the biceps brachii compared to other exercises for the same muscle group will likely remain consistent throughout a training cycle. However, it is essential to note that other muscles may have different characteristics, and strength training movements requiring individual muscle synergy patterns may affect reliability. Therefore, further research is encouraged to examine this relationship.

CHAPTER 7: REFERENCES

- Aagaard, P., Bojsen-Møller, J., & Lundbye-Jensen, J. (2020). Assessment of Neuroplasticity With Strength Training. In *Exercise and Sport Sciences Reviews* (Vol. 48, Issue 4, pp. 151–162). Lippincott Williams and Wilkins. <https://doi.org/10.1249/JES.0000000000000229>
- Al-Amri, M., Nicholas, K., Button, K., Sparkes, V., Sheeran, L., & Davies, J. L. (2018). Inertial Measurement Units for Clinical Movement Analysis: Reliability and Concurrent Validity. In *Sensors (Basel, Switzerland)* (Vol. 18, Issue 3, p. 719). MDPI AG. <https://doi.org/10.3390/s18030719>
- Alhammoud, M., Girard, O., Hansen, C., Racinais, S., Meyer, F., Hautier, C. A., & Morel, B. (2022). Repeated practice runs during on-snow training do not generate any measurable neuromuscular alterations in elite alpine skiers . In *Frontiers in Sports and Active Living* (Vol. 4, p. 829195). Frontiers Media S.A. <https://doi.org/10.3389/fspor.2022.829195>
- Alkner, B. A., & Bring, D. K. I. (2019). Muscle activation during gravity-independent resistance exercise compared to common exercises. In *Aerospace Medicine and Human Performance* (Vol. 90, Issue 6, pp. 506–512). Aerospace Medical Association. <https://doi.org/10.3357/AMHP.5097.2019>
- Alkner, B. A., Tesch, P. A., & Berg, H. E. (2000). Quadriceps EMG/force relationship in knee extension and leg press. In *Medicine and science in sports and exercise* (Vol. 32, Issue 2, pp. 459–463). Lippincott Williams & Wilkins. <https://doi.org/10.1097/00005768-200002000-00030>
- Amarantini, D., & Bru, B. (2015). Training-related changes in the EMG–moment relationship during isometric contractions: Further evidence of improved control of muscle activation in strength-trained men? In *Journal of Electromyography and Kinesiology* (Vol. 25, Issue 4, pp. 697–702). Elsevier Ltd. <https://doi.org/10.1016/j.jelekin.2015.04.002>
- Andersen, L. L., Andersen, J. L., Magnusson, S. P., & Aagaard, P. (2005). Neuromuscular adaptations to detraining following resistance training in previously untrained subjects. In *European journal of applied physiology* (Vol. 93, Issues 5–6, pp. 511–518). Springer Nature B.V. <https://doi.org/10.1007/s00421-004-1297-9>

- Bagchi, A., & Raizada, S. (2019). A comparative electromyographical analysis of biceps brachii and brachioradialis during eight different types of biceps curl. *Indian Journal of Public Health, 10*(5), 730–735.
- Ball, N., & Scurr, J. (2010). An assessment of the reliability and standardisation of tests used to elicit reference muscular actions for electromyographical normalisation. *Journal of Electromyography and Kinesiology, 20*(1), 81–88. <https://doi.org/10.1016/j.jelekin.2008.09.004>
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software, 67*(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Behm, D. G. (1995). Neuromuscular Implications and Applications of Resistance Training. *Journal of Strength and Conditioning Research, 9*(4), 264–274.
- Bemben, M. G., & Murphy, R. E. (2001). Age related neural adaptation following short term resistance training in women. *The Journal of Sports Medicine and Physical Fitness, 41*(3), 291–299. <http://www.ncbi.nlm.nih.gov/pubmed/11533557>
- Besomi, M., Hodges, P. W., Clancy, E. A., Van Dieën, J., Hug, F., Lowery, M., Merletti, R., Søgaard, K., Wrigley, T., Besier, T., Carson, R. G., Disselhorst-Klug, C., Enoka, R. M., Falla, D., Farina, D., Gandevia, S., Holobar, A., Kiernan, M. C., McGill, K., ... Tucker, K. (2020). Consensus for experimental design in electromyography (CEDE) project: Amplitude normalization matrix. *Journal of Electromyography and Kinesiology, 53*, 102438–102438. <https://doi.org/10.1016/j.jelekin.2020.102438>
- Bhullar, H. K., Loudon, G. H., Fothergill, J. C., & Jones, N. B. (1990). 1990 H Bhullar - Selective noninvasive electrode to study myoelectr [retrieved_2023-07-15]. *Medical and Biological Engineering and Computing, 28*, 581-586., 28, 581–586.
- Bolgia, L. A., & Uhl, T. L. (2007). Reliability of electromyographic normalization methods for evaluating the hip musculature. *Journal of Electromyography and Kinesiology, 17*(1), 102–111. <https://doi.org/10.1016/j.jelekin.2005.11.007>

- Boyer, A., Hug, F., Avrillon, S., & Lacourpaille, L. (2021). Individual differences in the distribution of activation among the hamstring muscle heads during stiff-leg Deadlift and Nordic hamstring exercises. *Journal of Sports Sciences*, *39*(16), 1830–1837.
<https://doi.org/10.1080/02640414.2021.1899405>
- Brandt, M., Andersen, L. L., Samani, A., Jakobsen, M. D., & Madeleine, P. (2017). Inter-day reliability of surface electromyography recordings of the lumbar part of erector spinae longissimus and trapezius descendens during box lifting. *BMC Musculoskeletal Disorders*, *18*(1).
<https://doi.org/10.1186/s12891-017-1872-y>
- Brooks, M., Kristensen, K., Benthem, K., Magnusson, A., Berg, C., Nielsen, A., Skaug, H., Mächler, M., & Bolker, B. (2017). glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal*, *9*(2), 378. <https://doi.org/10.32614/RJ-2017-066>
- Buchanan, T. S., Rovai, G. P., & Rymer, W. Z. (1989). Strategies for Muscle Activation During Isometric Torque Generation at the Human Elbow. *Journal of Neurophysiology*, *62*(6).
- Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *20*(6), 1023–1035.
<https://doi.org/10.1016/j.jelekin.2010.07.004>
- Calder, K. M., Hall, L.-A., Lester, S. M., Inglis, J. G., & Gabriel, D. A. (2005). Reliability of the biceps brachii M-wave. *Journal of Neuroengineering and Rehabilitation*, *2*(1), 33–33.
<https://doi.org/10.1186/1743-0003-2-33>
- Carroll, T. J., Riek, S., & Carson, R. G. (2001). Neural Adaptations to Resistance Training. *Sports Medicine*, *31*(12), 829–840. <https://doi.org/10.2165/00007256-200131120-00001>

- Carroll, T. J., Riek, S., & Carson, R. G. (2002). The sites of neural adaptation induced by resistance training in humans. *The Journal of Physiology*, *544*(Pt 2), 641–652.
<https://doi.org/10.1113/jphysiol.2002.024463>
- Casolo, A., Del Vecchio, A., Balshaw, T. G., Maeo, S., Lanza, M. B., Felici, F., Folland, J. P., & Farina, D. (2021). Behavior of motor units during submaximal isometric contractions in chronically strength-trained individuals. *Journal of Applied Physiology*, *131*(5), 1584–1598.
<https://doi.org/10.1152/jappphysiol.00192.2021>
- Chen, Y., Fu, C., Leung, W. S. W., & Shi, L. (2020). Drift-Free and Self-Aligned IMU-Based Human Gait Tracking System with Augmented Precision and Robustness. *IEEE Robotics and Automation Letters*, *5*(3), 4671–4678. <https://doi.org/10.1109/LRA.2020.3002203>
- Cheung, V. C. K., Ha, S. C. W., Zhang-Lea, J. H., Chan, Z. Y. S., Teng, Y., Yeung, G., Wu, L., Liang, D., & Cheung, R. T. H. (2024). Motor patterns of patients with spinal muscular atrophy suggestive of sensory and corticospinal contributions to the development of locomotor muscle synergies. *Journal of Neurophysiology*, *131*(2), 338–359. <https://doi.org/10.1152/jn.00513.2022>
- Christie, A. D., Foulis, S. A., & Kent, J. A. (2016). ATP cost of muscle contraction is associated with motor unit discharge rate in humans. *Neuroscience Letters*, *629*, 186–188.
<https://doi.org/10.1016/j.neulet.2016.07.007>
- Claiborne, T. L., Timmons, M. K., & Pincivero, D. M. (2009). Test–retest reliability of cardinal plane isokinetic hip torque and EMG. *Journal of Electromyography and Kinesiology*, *19*(5), e345–e352.
<https://doi.org/10.1016/j.jelekin.2008.07.005>
- Clancy, E. A., Morin, E. L., & Merletti, R. (2002). Sampling, noise-reduction and amplitude estimation issues in surface electromyography. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *12*(1), 1–16.
[https://doi.org/10.1016/s1050-6411\(01\)00033-5](https://doi.org/10.1016/s1050-6411(01)00033-5)

- Cleather, D. J., & Guthrie, S. R. (2007). Quantifying delayed-onset muscle soreness: A comparison of unidimensional and multidimensional instrumentation. *Journal of Sports Sciences*, 25(8), 845–850. <https://doi.org/10.1080/02640410600908050>
- Clemente, F., Badicu, G., Hasan, U. C., Akyildiz, Z., Pino-Ortega, J., Silva, R., & Rico-González, M. (2022). Validity and reliability of inertial measurement units for jump height estimations: a systematic review. *Human Movement*, 23(4), 1–20. <https://doi.org/10.5114/hm.2023.111548>
- Coratella, G., Tornatore, G., Longo, S., Toninelli, N., Padovan, R., Esposito, F., & Cè, E. (2023). Biceps Brachii and Brachioradialis Excitation in Biceps Curl Exercise: Different Handgrips, Different Synergy. *Sports*, 11(3), 64. <https://doi.org/10.3390/sports11030064>
- Costa-Santos, C., Bernardes, J., Ayres-de-Campos, D., Costa, A., & Costa, C. (2011). The limits of agreement and the intraclass correlation coefficient may be inconsistent in the interpretation of agreement. *Journal of Clinical Epidemiology*, 64(3), 264–269.
- Criswell, E. (2010). *Cram's introduction to surface electromyography*. (2nd ed.). Jones & Bartlett Publishers.
- Croskery, M. (2004). *Weight training for a new body: over 300 exercises to tone, strengthen and build muscle* [Book]. MyoMax Performance.
- Crouzier, M., Hug, F., Dorel, S., Deschamps, T., Tucker, K., & Lacourpaille, L. (2019). Do individual differences in the distribution of activation between synergist muscles reflect individual strategies? *Experimental Brain Research*, 237(3), 625–635. <https://doi.org/10.1007/s00221-018-5445-6>
- Cutsem, M. Van, Feiereisen, P., Duchateau, J., & Hainaut, K. (1997). Mechanical Properties and Behaviour of Motor Units in the Tibialis Anterior During Voluntary Contractions. *Canadian Journal of Applied Physiology*, 22(6), 585–597. <https://doi.org/10.1139/h97-038>

- Daly, C., Lafferty, E., Joyce, M., & Malone, A. (2019). Determining the most effective exercise for gluteal muscle activation in children with cerebral palsy using surface electromyography. *Gait & Posture*, *70*, 270–274. <https://doi.org/10.1016/j.gaitpost.2019.03.013>
- de Araújo, R. C., Tucci, H. T., de Andrade, R., Martins, J., Bevilacqua-Grossi, D., & de Oliveira, A. S. (2009). Reliability of electromyographic amplitude values of the upper limb muscles during closed kinetic chain exercises with stable and unstable surfaces. *Journal of Electromyography and Kinesiology*, *19*(4), 685–694. <https://doi.org/10.1016/j.jelekin.2007.11.014>
- De Luca, C. J. (1997). The Use of Surface Electromyography in Biomechanics. *Journal of Applied Biomechanics*, *13*(2), 135–163. <https://doi.org/10.1123/jab.13.2.135>
- De Luca, C. J., LeFever, R. S., McCue, M. P., & Xenakis, A. P. (1982). Behaviour of human motor units in different muscles during linearly varying contractions. *The Journal of Physiology*, *329*(1), 113–128. <https://doi.org/10.1113/jphysiol.1982.sp014293>
- De Ridder, R., Lebleu, J., Willems, T., De Blaiser, C., Detrembleur, C., & Roosen, P. (2019). Concurrent Validity of a Commercial Wireless Trunk Triaxial Accelerometer System for Gait Analysis. *Journal of Sport Rehabilitation*, *28*(6). <https://doi.org/10.1123/JSR.2018-0295>
- Del Vecchio, A., Casolo, A., Negro, F., Scorcelletti, M., Bazzucchi, I., Enoka, R., Felici, F., & Farina, D. (2019). The increase in muscle force after 4 weeks of strength training is mediated by adaptations in motor unit recruitment and rate coding. *The Journal of Physiology*, *597*(7), 1873–1887. <https://doi.org/10.1113/JP277250>
- Delgado, J., Drinkwater, E. J., Banyard, H. G., Haff, G. G., & Nosaka, K. (2019). *Comparison Between Back Squat, Romanian Deadlift, and Barbell Hip Thrust for Leg and Hip Muscle Activities During Hip Extension*. www.nsc.com
- Deschenes, M. R., McCoy, R. W., Holdren, A. N., & Eason, M. K. (2009). Gender influences neuromuscular adaptations to muscle unloading. *European Journal of Applied Physiology*, *105*(6), 889–897. <https://doi.org/10.1007/s00421-008-0974-5>

- Dideriksen, J. L., & Farina, D. (2019). Amplitude cancellation influences the association between frequency components in the neural drive to muscle and the rectified EMG signal. *PLoS Computational Biology*, *15*(5). <https://doi.org/10.1371/journal.pcbi.1006985>
- Duchateau, J., Semmler, J. G., & Enoka, R. M. (2006). Training adaptations in the behavior of human motor units.. *Journal of Applied Physiology (Bethesda, Md. : 1985)*, *101*(6), 1766–1775. <https://doi.org/10.1152/jappphysiol.00543.2006>
- Eager, D., Pendrill, A.-M., & Reistad, N. (2016). Beyond velocity and acceleration: jerk, snap and higher derivatives. *European Journal of Physics*, *37*(6), 65008. <https://doi.org/10.1088/0143-0807/37/6/065008>
- Eldridge, S. M., Ukoumunne, O. C., & Carlin, J. B. (2009). The Intra-Cluster Correlation Coefficient in Cluster Randomized Trials: A Review of Definitions. *International Statistical Review*, *77*(3), 378–394. <https://doi.org/10.1111/j.1751-5823.2009.00092.x>
- Elgueta-Cancino, E., Evans, E., Martinez-Valdes, E., & Falla, D. (2022). The Effect of Resistance Training on Motor Unit Firing Properties: A Systematic Review and Meta-Analysis. *Frontiers in Physiology*, *13*, 817631–817631. <https://doi.org/10.3389/fphys.2022.817631>
- Ema, R., Wakahara, T., Miyamoto, N., Kanehisa, H., & Kawakami, Y. (2013). Inhomogeneous architectural changes of the quadriceps femoris induced by resistance training. *European Journal of Applied Physiology*, *113*(11), 2691–2703. <https://doi.org/10.1007/s00421-013-2700-1>
- Enoka, R. M., & Duchateau, J. (2016). Physiology of Muscle Activation and Force Generation [Bookitem]. In *Surface Electromyography : Physiology, Engineering, and Applications* (1st ed., pp. 1–29). Wiley. <https://doi.org/10.1002/9781119082934.ch01>
- Ethier, J. (2022, November 15). *We tested 16 Exercises, these are the best for growth [Video]*. Youtube. <https://youtu.be/wh-KKiOXY34>

- Fan, J. Z., Liu, X., & Ni, G. X. (2014). Angular velocity affects trunk muscle strength and EMG activation during isokinetic axial rotation. *BioMed Research International*, 2014. <https://doi.org/10.1155/2014/623191>
- Farina, D. (2006). Interpretation of the surface electromyogram in dynamic contractions. *Exercise and Sport Sciences Reviews*, 34(3), 121–127. <https://doi.org/10.1249/00003677-200607000-00006>
- Farina, D., Merletti, R., & Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, 96(4), 1486–1495. <https://doi.org/10.1152/jappphysiol.01070.2003>
- Farina, D., & Negro, F. (2015). Common synaptic input to motor neurons, motor unit synchronization, and force control. *Exercise and Sport Sciences Reviews*, 43(1), 23–33. <https://doi.org/10.1249/jes.0000000000000032>
- Farina, D., Negro, F., & Dideriksen, J. L. (2014). The effective neural drive to muscles is the common synaptic input to motor neurons. *The Journal of Physiology*, 592(16), 3427–3441. <https://doi.org/10.1113/jphysiol.2014.273581>
- Farina, D., Stegeman, D. F., & Merletti, R. (2016). Biophysics of the Generation of EMG Signals [Bookitem]. In *Surface Electromyography* (1st ed., pp. 1–24). Wiley. <https://doi.org/10.1002/9781119082934.ch02>
- Fleiss, J. L. (1999). *The design and analysis of clinical experiments* [Book]. Wiley.
- Folland, J. P., & Williams, A. G. (2007). The Adaptations to Strength Training. *Sports Medicine*, 37(2), 145–168. <https://doi.org/10.2165/00007256-200737020-00004>
- Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. *Frontiers in Computational Neuroscience*, 6, 99–99. <https://doi.org/10.3389/fncom.2012.00099>
- Fukuda, T. Y., Echeimberg, J. O., Pompeu, J. E., Garcia Lucareli, P. R., Garbelotti, S., Gimenes, R. O., & Apolinario, A. (2010). Root Mean Square value of the electromyographic signal in the isometric

- torque of the quadriceps, hamstrings and brachial biceps muscles in female subjects. *The Journal of Applied Research*, 10(1), 32.
- Gardiner, P. F. (2011). *Advanced neuromuscular exercise physiology* [Book]. Human Kinetics.
- Gaudet, G., Raison, M., Maso, F. D., Achiche, S., & Begon, M. (2016). Intra- and Intersession Reliability of Surface Electromyography on Muscles Actuating the Forearm During Maximum Voluntary Contractions. *Journal of Applied Biomechanics*, 32(6), 558–570. <https://doi.org/10.1123/jab.2015-0214>
- Giraudeau, B. (1996). Negative values of the intraclass correlation coefficient are not theoretically possible. *Journal of Clinical Epidemiology*, 49(10), 1205–1205. [https://doi.org/10.1016/0895-4356\(96\)00053-4](https://doi.org/10.1016/0895-4356(96)00053-4)
- Giuriato, G., Romanelli, M. G., Bartolini, D., Vernillo, G., Pedrinolla, A., Moro, T., Franchi, M., Locatelli, E., Andani, M. E., Laginestra, F. G., Barbi, C., Aloisi, G. F., Cavedon, V., Milanese, C., Orlandi, E., De Simone, T., Fochi, S., Patuzzo, C., Malerba, G., ... Venturelli, M. (2024). Sex differences in neuromuscular and biological determinants of isometric maximal force. *Acta Physiologica (Oxford, England)*, 240(4), e14118. <https://doi.org/10.1111/apha.14118>
- Gollhofer, A., Horstmann, G. A., Schmidtbleicher, D., & Schönthal, D. (1990). Reproducibility of electromyographic patterns in stretch-shortening type contractions. *European Journal of Applied Physiology and Occupational Physiology*, 60(1), 7–14. <https://doi.org/10.1007/BF00572179>
- Goodwin, P. C., Koorts, K., Mack, R., Mai, S., Morrissey, M. C., & Hooper, D. M. (1999). Reliability of leg muscle electromyography in vertical jumping. *European Journal of Applied Physiology and Occupational Physiology*, 79(4), 374–378. <https://doi.org/10.1007/s004210050523>
- Grime, A., Daines, S., Pringle, L., Heang, L., & Ribeiro, D. C. (2018). The within-day reliability of scapular and shoulder emg measurements in asymptomatic individuals during shoulder abduction. *New Zealand Journal of Physiotherapy*, 46(2), 67–72. <https://doi.org/10.15619/NZJP/46.2.02>

- Guilhem, G., Cornu, C., & Guével, A. (2011). Muscle architecture and EMG activity changes during isotonic and isokinetic eccentric exercises. *European Journal of Applied Physiology*, *111*(11), 2723–2733. <https://doi.org/10.1007/s00421-011-1894-3>
- Haahr, M. (2024, April 16). *Random.org - List Randomizer*. RANDOM.ORG: True Random Number Service. <https://www.random.org/lists/>
- Haff, G., & Triplett, N. T. (2016). *Essentials of strength training and conditioning* (G. Haff & N. T. Triplett, Eds.; Fourth edition.) [Book]. Human Kinetics.
- Hägg, G. M., Melin, B., & Kadefors, R. (2005). Applications in Ergonomics. In *Electromyography* (pp. 343–363). John Wiley & Sons, Inc. <https://doi.org/10.1002/0471678384.ch13>
- Häkkinen, K., Pakarinen, A., & Kallinen, M. (1992). Neuromuscular adaptations and serum hormones in women during short-term intensive strength training. *European Journal of Applied Physiology and Occupational Physiology*, *64*(2), 106–111. <https://doi.org/10.1007/BF00717946>
- Hayat, M. J., & Hedlin, H. (2012). Modern statistical modeling approaches for analyzing repeated-measures data. *Nursing Research*, *61*(3), 188–194. <https://doi.org/10.1097/NNR.0b013e31824f5f58>
- Henneman, E., Somjen, G., & Carpenter, D. O. (1965). Excitability and inhibitability of motoneurons of different sizes. *Journal of Neurophysiology*, *28*(3), 599–620. <https://doi.org/10.1152/jn.1965.28.3.599>
- Herda, T. J. (2022). Resistance exercise training and the motor unit. *European Journal of Applied Physiology*, *122*(9), 2019–2035. <https://doi.org/10.1007/s00421-022-04983-7>
- Herda, T. J., Holmes, E. A., Cleary, C. J., Minor, K. T., Thyfault, J. P., Shook, R. P., & Herda, A. A. (2024). Motor unit firing rates increase in prepubescent youth following linear periodization resistance exercise training. *European Journal of Applied Physiology*. <https://doi.org/10.1007/s00421-024-05455-w>

- Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, *10*(5), 361–374. [https://doi.org/10.1016/S1050-6411\(00\)00027-4](https://doi.org/10.1016/S1050-6411(00)00027-4)
- Hester, G. M., Pope, Z. K., Benik, F. M., & DeFreitas, J. M. (2016). Effects of Short-term Strength Training on Maximal Motor Unit Firing Rates and Antagonist Co-activation. *Medicine & Science in Sports & Exercise*, *48*, 406. <https://doi.org/10.1249/01.mss.0000486224.41013.8e>
- Hirono, T., Igawa, K., Okudaira, M., Takeda, R., Nishikawa, T., & Watanabe, K. (2024). Time-of-day effects on motor unit firing and muscle contractile properties in humans. *Journal of Neurophysiology*, *131*(3), 472–479. <https://doi.org/10.1152/jn.00368.2023>
- Hodson-Tole, E. F., & Wakeling, J. M. (2009). Motor unit recruitment for dynamic tasks: current understanding and future directions. *Journal of Comparative Physiology B*, *179*(1), 57–66. <https://doi.org/10.1007/s00360-008-0289-1>
- Howatson, G., & Van Someren, K. A. (2005). The reproducibility of peak isometric torque and electromyography activity in unfamiliarised subjects using isokinetic dynamometry on repeated days. In *Isokinetics and Exercise Science* (Vol. 13). IOS Press.
- Huebner, A., McGinn, T., & Sisk, M. (2021). *psr: Functions for Analyzing Performance Science Data*.
- Hug, F., Turpin, N. A., Guevel, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of Applied Physiology*, *108*(6), 1727–1736. <https://doi.org/10.1152/jappphysiol.01305.2009>
- Humiston, R. (2022, October 27). *You're Training Triceps Wrong | Backed by Science*. [Video]. Youtube. <https://youtu.be/KtYVMWx2iAg>
- Hutchinson, T. E., White, G., Iqbal, K., & Singh, R. E. (2018). A Systematic Review on Muscle Synergies: From Building Blocks of Motor Behavior to a Neurorehabilitation Tool. *Applied Bionics and Biomechanics*, *2018*(2018), 1–15. <https://doi.org/10.1155/2018/3615368>

- Jakobsen, T. L., Jakobsen, M. D., Andersen, L. L., Husted, H., Kehlet, H., & Bandholm, T. (2019). Quadriceps muscle activity during commonly used strength training exercises shortly after total knee arthroplasty: implications for home-based exercise-selection. *Journal of Experimental Orthopaedics*, 6(1), 29–12. <https://doi.org/10.1186/s40634-019-0193-5>
- Jenkins, N. D. M., Housh, T. J., Bergstrom, H. C., Cochrane, K. C., Hill, E. C., Smith, C. M., Johnson, G. O., Schmidt, R. J., & Cramer, J. T. (2015). Muscle activation during three sets to failure at 80 vs. 30 % 1RM resistance exercise. *European Journal of Applied Physiology*, 115(11), 2335–2347. <https://doi.org/10.1007/s00421-015-3214-9>
- Jenkins, N. D. M., Miramonti, A. A., Hill, E. C., Smith, C. M., Cochrane-Snyman, K. C., Housh, T. J., & Cramer, J. T. (2017). Greater neural adaptations following high- vs. low-load resistance training. *Frontiers in Physiology*, 8(MAY). <https://doi.org/10.3389/fphys.2017.00331>
- Jensen, C., & Westgaard, R. H. (1995). Functional subdivision of the upper trapezius muscle during maximal isometric contractions. *Journal of Electromyography and Kinesiology*, 5(4), 227–237. [https://doi.org/10.1016/1050-6411\(94\)00011-5](https://doi.org/10.1016/1050-6411(94)00011-5)
- Jensen, T. E., Leutert, R., Rasmussen, S. T., Mouatt, J. R., Christiansen, M. L. B., Jensen, B. R., & Richter, E. A. (2012). EMG-Normalised kinase activation during exercise is higher in human gastrocnemius compared to soleus muscle. *PLoS ONE*, 7(2). <https://doi.org/10.1371/journal.pone.0031054>
- Jesunathadas, M., Marmon, A. R., Gibb, J. M., & Enoka, R. M. (2010). Recruitment and derecruitment characteristics of motor units in a hand muscle of young and old adults. *Journal of Applied Physiology (1985)*, 108(6), 1659–1667. <https://doi.org/10.1152/jappphysiol.00807.2009>
- Joanisse, S., Lim, C., McKendry, J., Mcleod, J. C., Stokes, T., & Phillips, S. M. (2020). Recent advances in understanding resistance exercise training-induced skeletal muscle hypertrophy in humans. In *F1000Research* (Vol. 9). F1000 Research Ltd. <https://doi.org/10.12688/f1000research.21588.1>

- Jobson, S. A., Hopker, J., Arkesteijn, M., & Passfield, L. (2013). Inter- and intra-session reliability of muscle activity patterns during cycling. *Journal of Electromyography and Kinesiology*, 23(1), 230–237. <https://doi.org/10.1016/j.jelekin.2012.08.013>
- Judge, L. W., Moreau, C., & Burke, J. R. (2003). Neural adaptations with sport-specific resistance training in highly skilled athletes. *Journal of Sports Sciences*, 21(5), 419–427. <https://doi.org/10.1080/0264041031000071173>
- Kamen, G., & Caldwell, G. E. (1996). Physiology and interpretation of the electromyogram. *Journal of Clinical Neurophysiology: Official Publication of the American Electroencephalographic Society*, 13(5), 366–384. <https://doi.org/10.1097/00004691-199609000-00002>
- Kamen, G., & Knight, C. A. (2004). Training-Related Adaptations in Motor Unit Discharge Rate in Young and Older Adults. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 59(12), 1334–1338. <https://doi.org/10.1093/gerona/59.12.1334>
- Kamen, Gary. (2010). *Essentials of electromyography* (D. A. Gabriel, Ed.) [Book]. Human Kinetics.
- Karaborklu Argut, S., Celik, D., & Yasacı, Z. (2022). Effectiveness of therapeutic electromyographic biofeedback after orthopedic knee surgeries: a systematic review. *Disability and Rehabilitation*, 44(14), 3364–3372. <https://doi.org/10.1080/09638288.2020.1867904>
- Kawakami, Y., Abe, T., Kuno, S. Y., & Fukunaga, T. (1995). Training-induced changes in muscle architecture and specific tension. *European Journal of Applied Physiology and Occupational Physiology*, 72(1–2), 37–43. <https://doi.org/10.1007/BF00964112>
- Keenan, K. G., Farina, D., Maluf, K. S., Merletti, R., & Enoka, R. M. (2005). Influence of amplitude cancellation on the simulated surface electromyogram. *Journal of Applied Physiology*, 98(1), 120–131. <https://doi.org/10.1152/jappphysiol.00894.2004>

- Kellis, E., & Katis, A. (2008). Reliability of EMG power-spectrum and amplitude of the semitendinosus and biceps femoris muscles during ramp isometric contractions. *Journal of Electromyography and Kinesiology*, 18(3), 351–358. <https://doi.org/10.1016/j.jelekin.2006.12.001>
- Kleiber, T., Kunz, L., & Disselhorst-Klug, C. (2015). Muscular coordination of biceps brachii and brachioradialis in elbow flexion with respect to hand position. *Frontiers in Physiology*, 6, 215–215. <https://doi.org/10.3389/fphys.2015.00215>
- Kleiner, A. F. R., Pacifici, I., Vagnini, A., Camerota, F., Celletti, C., Stocchi, F., De Pandis, M. F., & Galli, M. (2018). Timed Up and Go evaluation with wearable devices: Validation in Parkinson's disease. *Journal of Bodywork and Movement Therapies*, 22(2), 390–395. <https://doi.org/10.1016/j.jbmt.2017.07.006>
- Kohn, S., Smart, R. R., & Jakobi, J. M. (2018). Voluntary activation and twitch potentiation of the elbow flexors across supinated, neutral, and pronated forearm orientations. *Physiological Reports*, 6(1), e13560-n/a. <https://doi.org/10.14814/phy2.13560>
- Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, 15(2), 155–163. <https://doi.org/10.1016/j.jcm.2016.02.012>
- Kossev, A., & Christova, P. (1998). Discharge pattern of human motor units during dynamic concentric and eccentric contractions. *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control*, 109(3), 245–255. [https://doi.org/10.1016/S0924-980X\(98\)00012-5](https://doi.org/10.1016/S0924-980X(98)00012-5)
- Kristiansen, M., Madeleine, P., Hansen, E. A., & Samani, A. (2015). Inter-subject variability of muscle synergies during bench press in power lifters and untrained individuals. *Scandinavian Journal of Medicine & Science in Sports*, 25(1), 89–97. <https://doi.org/10.1111/sms.12167>
- Kristiansen, M., Samani, A., Madeleine, P., & Hansen, E. A. (2016). Muscle synergies during bench press are reliable across days. *Journal of Electromyography and Kinesiology : Official Journal of the*

International Society of Electrophysiological Kinesiology, 30, 81–88.

<https://doi.org/10.1016/j.jelekin.2016.06.004>

Kukulka, C. G., & Clamann, H. P. (1981). Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. *Brain Research*, 219(1), 45–55. [https://doi.org/10.1016/0006-8993\(81\)90266-3](https://doi.org/10.1016/0006-8993(81)90266-3)

Kumar, S., Singh, J., Pradhan, P., Kumar, S., & Thapa, R. K. (2023). Validity and Reliability of an Inertial Measurement Unit (BTS G-Walk) for Measurement of Countermovement Jump Height: A pilot-study. *J. Anthr. Sport Phys. Educ*, 7. <https://doi.org/10.26773/jaspe.230704>

Lacerda, L. T., Marra-Lopes, R. O., Lanza, M. B., Diniz, R. C. R., Lima, F. V., Martins-Costa, H. C., Pedrosa, G. F., Andrade, A. G. P., Kibele, A., & Chagas, M. H. (2021). Resistance training with different repetition duration to failure: Effect on hypertrophy, strength and muscle activation. *PeerJ*, 9. <https://doi.org/10.7717/peerj.10909>

Larsson, B., Månsson, B., Karlberg, C., Syvertsson, P., Elert, J., & Gerdle, B. (1999). Reproducibility of surface EMG variables and peak torque during three sets of ten dynamic contractions. In *Journal of Electromyography and Kinesiology* (Vol. 9). www.elsevier.com/locate/jelekin

Lasevicius, T., Ugrinowitsch, C., Schoenfeld, B. J., Roschel, H., Tavares, L. D., De Souza, E. O., Laurentino, G., & Tricoli, V. (2018). Effects of different intensities of resistance training with equated volume load on muscle strength and hypertrophy. *European Journal of Sport Science*, 18(6), 772–780. <https://doi.org/10.1080/17461391.2018.1450898>

Lau, W. Y., Blazeovich, A. J., Newton, M. J., Wu, S. S. X., & Nosaka, K. (2021). Effects of wrist position on eccentric exercise-induced muscle damage of the elbow flexors. *Scandinavian Journal of Medicine and Science in Sports*, 31(6), 1290–1300. <https://doi.org/10.1111/sms.13936>

Lee, K. A., Hicks, G., & Nino-Murcia, G. (1991). Validity and reliability of a scale to assess fatigue. *Psychiatry Research*, 36(3), 291–298. [https://doi.org/10.1016/0165-1781\(91\)90027-M](https://doi.org/10.1016/0165-1781(91)90027-M)

- Lenth, R., Bolker, B., Buerkner, P., Giné-Vázquez, I., Herve, M., Jung, M., Love, J., Miguez, F., Riebl, H., & Singmann, H. (2024). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (1.10.1). R Package. <https://CRAN.R-project.org/package=emmeans>
- Lim, C., Nunes, E. A., Currier, B. S., McLeod, J. C., Thomas, A. C. Q., & Phillips, S. M. (2022). An Evidence-Based Narrative Review of Mechanisms of Resistance Exercise-Induced Human Skeletal Muscle Hypertrophy. *Medicine and Science in Sports and Exercise*, *54*(9), 1546–1559. <https://doi.org/10.1249/MSS.0000000000002929>
- Lopez, P., Radaelli, R., Taaffe, D. R., Newton, R. U., Galvão, D. A., Trajano, G. S., Teodoro, J. L., Kraemer, W. J., Häkkinen, K., & Pinto, R. S. (2021). Resistance Training Load Effects on Muscle Hypertrophy and Strength Gain: Systematic Review and Network Meta-analysis. In *Medicine and Science in Sports and Exercise* (Vol. 53, Issue 6, pp. 1206–1216). Lippincott Williams and Wilkins. <https://doi.org/10.1249/MSS.0000000000002585>
- Mao, S., Takahashi, T., Takai, Y., & Kanehisa, H. (2013). Trainability of muscular activity level during maximal voluntary co-contraction: comparison between bodybuilders and nonathletes. *PLoS One*, *8*(11), e79486–e79486. <https://doi.org/10.1371/journal.pone.0079486>
- Manca, A., Dragone, D., Dvir, Z., & Deriu, F. (2017). Cross-education of muscular strength following unilateral resistance training: a meta-analysis. *European Journal of Applied Physiology*, *117*(11), 2335–2354. <https://doi.org/10.1007/s00421-017-3720-z>
- Mathur, S., Eng, J. J., & MacIntyre, D. L. (2005). Reliability of surface EMG during sustained contractions of the quadriceps. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *15*(1), 102–110. <https://doi.org/10.1016/j.jelekin.2004.06.003>
- Mattan, B.-S., Ludecke, D., & Makowski, D. (2020). Estimation of Effect Size Indices and Standardized Parameters. *Journal of Open Source Software*, *5*(56), 2815. <https://doi.org/10.21105/joss.02815>

- Mavor, M. P., Chan, V. C. H., Gruevski, K. M., Bossi, L. L. M., Karakolis, T., & Graham, R. B. (2023). Assessing the Soldier Survivability Tradespace Using a Single IMU. *IEEE Access*, 1–1.
<https://doi.org/10.1109/ACCESS.2023.3286305>
- McGinn, T., Huebner, A., & Sisk, M. (2021, April 4). *psr Explained*. Rdr.io.
<https://rdr.io/cran/psr/f/inst/doc/psr-explained.Rmd>
- McHugh, M. P., Clifford, T., Abbott, W., Kwicien, S. Y., Kremenec, I. J., DeVita, J. J., & Howatson, G. (2019). Countermovement Jump Recovery in Professional Soccer Players Using an Inertial Sensor. *International Journal of Sports Physiology and Performance*, 14(1), 1–15.
<https://doi.org/10.1123/ijsp.2018-0131>
- Merletti, R. (2000). Surface electromyography: The SENIAM project. *Europa Medicophysica*, 36(4), 167.
<https://doi.org/info:doi/>
- Merletti, R., Fiorito, A., Lo Conte, L. R., & Cisari, C. (1998). Repeatability of electrically evoked EMG signals in the human vastus medialis muscle. *Muscle & Nerve*, 21(2), 184–193.
[https://doi.org/10.1002/\(SICI\)1097-4598\(199802\)21:2<184::AID-MUS5>3.0.CO;2-7](https://doi.org/10.1002/(SICI)1097-4598(199802)21:2<184::AID-MUS5>3.0.CO;2-7)
- Merletti, R., Lo Conte, L. R., & Sathyan, D. (1995). Repeatability of electrically-evoked myoelectric signals in the human tibialis anterior muscle. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, 5(2), 67–80.
[https://doi.org/10.1016/1050-6411\(94\)00004-6](https://doi.org/10.1016/1050-6411(94)00004-6)
- Merletti, R., & Muceli, S. (2019). Tutorial. Surface EMG detection in space and time: Best practices. *Journal of Electromyography and Kinesiology*, 49, 102363–102363.
<https://doi.org/10.1016/j.jelekin.2019.102363>
- Merlo, A., & Campanini, I. (2010). Technical Aspects of Surface Electromyography for Clinicians. In *The Open Rehabilitation Journal* (Vol. 3).

- Mesin, L., Merletti, R., & Rainoldi, A. (2009). Surface EMG: The issue of electrode location. *Journal of Electromyography and Kinesiology*, 19(5), 719–726. <https://doi.org/10.1016/j.jelekin.2008.07.006>
- Milner-Brown, H. S., & Lee, R. G. (1975). Synchronization of human motor units: Possible roles of exercise and supraspinal reflexes. *Electroencephalography and Clinical Neurophysiology*, 38(3), 245–254. [https://doi.org/10.1016/0013-4694\(75\)90245-X](https://doi.org/10.1016/0013-4694(75)90245-X)
- Mobbs, R. J., Perring, J., Raj, S. M., Maharaj, M., Yoong, N. K. M., Sy, L. W., Fonseka, R. D., Natarajan, P., & Choy, W. J. (2022). Gait metrics analysis utilizing single-point inertial measurement units: a systematic review. In *mHealth* (Vol. 8). AME Publishing Company. <https://doi.org/10.21037/mhealth-21-17>
- Moore, K. L. (1992). *Muscles of the Arm. Clinically oriented anatomy* (3rd ed.) [Book]. Williams & Wilkins.
- Multer, C. E. (2002). *Gender comparisons in neural, morphological, and protein muscle markers of adaptation to acute resistance training* [Thesis (Ph. D.)]. Brigham Young University.
- Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination R² and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of the Royal Society Interface*, 14(134). <https://doi.org/10.1098/rsif.2017.0213>
- Neyroud, D., Kayser, B., & Place, N. (2015). Inappropriate interpretation of surface EMG signals and muscle fiber characteristics impedes understanding of the control of neuromuscular function. In *Journal of Applied Physiology* (Vol. 119, Issue 12, pp. 1516–1518). American Physiological Society. <https://doi.org/10.1152/jappphysiol.00280.2015>
- Nordander, C., Willner, J., Hansson, G.-A., Larsson, B., Unge, J., Granquist, L., & Skerfving, S. (2003). Influence of the subcutaneous fat layer, as measured by ultrasound, skinfold calipers and BMI, on the EMG amplitude. *European Journal of Applied Physiology*, 89(6), 514–519. <https://doi.org/10.1007/s00421-003-0819-1>

- Oliveira, D. S. de, Casolo, A., Balshaw, T. G., Maeo, S., Lanza, M. B., Martin, N. R. W., Maffulli, N., Kinfe, T. M., Eskofier, B. M., Folland, J. P., Farina, D., & Del Vecchio, A. (2022). Neural decoding from surface high-density EMG signals: influence of anatomy and synchronization on the number of identified motor units. *Journal of Neural Engineering*, *19*(4), 46029. <https://doi.org/10.1088/1741-2552/ac823d>
- Orth, M., Snijders, A. H., & Rothwell, J. C. (2003). The variability of intracortical inhibition and facilitation. *Clinical Neurophysiology*, *114*(12), 2362–2369. [https://doi.org/10.1016/S1388-2457\(03\)00243-8](https://doi.org/10.1016/S1388-2457(03)00243-8)
- Paoli, A., Mancin, L., Saoncella, M., Grigoletto, D., Pacelli, F. Q., Zamparo, P., Schoenfeld, B. J., & Marcolin, G. (2019). Mind-muscle connection: effects of verbal instructions on muscle activity during bench press exercise. *European Journal of Translational Myology*, *29*(2). <https://doi.org/10.4081/ejtm.2019.8250>
- Pearcey, G. E. P., Alizedah, S., Power, K. E., & Button, D. C. (2021). Chronic resistance training: is it time to rethink the time course of neural contributions to strength gain? *European Journal of Applied Physiology*, *121*(9), 2413–2422. <https://doi.org/10.1007/s00421-021-04730-4>
- Pearcey, G. E. P., Power, K. E., & Button, D. C. (2014). Differences in supraspinal and spinal excitability during various force outputs of the biceps brachii in chronic- and non-resistance trained individuals. *PloS One*, *9*(5), e98468. <https://doi.org/10.1371/journal.pone.0098468>
- Potvin, J. R. (1997). Effects of muscle kinematics on surface EMG amplitude and frequency during fatiguing dynamic contractions. *Journal of applied physiology*, *82*(1), 144-151.
- Potvin, J. R., & Brown, S. H. M. (2004). Less is more: high pass filtering, to remove up to 99% of the surface EMG signal power, improves EMG-based biceps brachii muscle force estimates. *Journal of Electromyography and Kinesiology*, *14*(3), 389–399. <https://doi.org/10.1016/j.jelekin.2003.10.005>

- Praagman, M., Chadwick, E. K. J., van der Helm, F. C. T., & Veeger, H. E. J. (2010). The effect of elbow angle and external moment on load sharing of elbow muscles. *Journal of Electromyography and Kinesiology*, 20(5), 912–922. <https://doi.org/10.1016/j.jelekin.2010.04.003>
- Praagman, M., Praagman, J., Chadwick, E. K. J., van der Helm, F. C. T., & Veeger, H. E. J. (2008). The effect of PCSA and moment arm distributions on the load sharing of arm muscles. *Muscle Load Sharing*, 85.
- Praagman, M., Veeger, H. E. J., Chadwick, E. K. J., Colier, W. N. J. M., & van der Helm, F. C. T. (2003). Muscle oxygen consumption, determined by NIRS, in relation to external force and EMG. *Journal of Biomechanics*, 36(7), 905–912. [https://doi.org/10.1016/S0021-9290\(03\)00081-2](https://doi.org/10.1016/S0021-9290(03)00081-2)
- Pucci, A. R., Griffin, L., & Cafarelli, E. (2006). Maximal motor unit firing rates during isometric resistance training in men. *Experimental Physiology*, 91(1), 171–178. <https://doi.org/10.1113/expphysiol.2005.032094>
- Rainoldi, A., Galardi, G., Maderna, L., Comi, G., Lo Conte, L., & Merletti, R. (1999). Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, 9(2), 105–119. [https://doi.org/10.1016/s1050-6411\(98\)00042-x](https://doi.org/10.1016/s1050-6411(98)00042-x)
- Rainoldi, A., Moritani, T., & Boccia, G. (2016). EMG in Exercise Physiology and Sports [Bookitem]. In R. Merletti & D. Farina (Eds.), *Surface Electromyography* (1st ed., pp. 501–539). Wiley. <https://doi.org/10.1002/9781119082934.ch19>
- Rainoldi, A., Nazzaro, M., Merletti, R., Farina, D., Caruso, I., & Gaudenti, S. (2000). Geometrical factors in surface EMG of the vastus medialis and lateralis muscles. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, 10(5), 327–336. [https://doi.org/10.1016/s1050-6411\(00\)00024-9](https://doi.org/10.1016/s1050-6411(00)00024-9)

- Reece, T. M., Arnold, C. E., & Herda, T. J. (2021). An examination of motor unit firing rates during steady torque of maximal efforts with either an explosive or slower rate of torque development. *Experimental Physiology*, *106*(12), 2517–2530. <https://doi.org/10.1113/EP089808>
- Richman, J., Makrides, L., & Prince, B. (1980). Research methodology and applied statistics. Part 3: measurement procedures in research. *Physiotherapy Canada*, *32*(4), 253–257.
- Riek, S., & Bawa, P. (1992). Recruitment of motor units in human forearm extensors. *Journal of Neurophysiology*, *68*(1), 100–108. <https://doi.org/10.1152/jn.1992.68.1.100>
- Roberts, M. D., Haun, C. T., Mobley, C. B., Mumford, P. W., Romero, M. A., Roberson, P. A., Vann, C. G., & McCarthy, J. J. (2018). Physiological differences between low versus high skeletal muscle hypertrophic responders to resistance exercise training: Current perspectives and future research directions. In *Frontiers in Physiology* (Vol. 9, Issue JUL). Frontiers Media S.A. <https://doi.org/10.3389/fphys.2018.00834>
- Ruple, B. A., Plotkin, D. L., Smith, M. A., Godwin, J. S., Sexton, C. L., McIntosh, M. C., Kontos, N. J., Beausejour, J. P., Pagan, J. I., Rodriguez, J. P., Sheldon, D., Knowles, K. S., Libardi, C. A., Young, K. C., Stock, M. S., & Roberts, M. D. (2023). The effects of resistance training to near failure on strength, hypertrophy, and motor unit adaptations in previously trained adults. *Physiological Reports*, *11*(9), e15679-n/a. <https://doi.org/10.14814/phy2.15679>
- Saeterbakken, A. H., Chaudhari, A., van den Tillaar, R., & Andersen, V. (2019). The effects of performing integrated compared to isolated core exercises. *PLoS ONE*, *14*(2). <https://doi.org/10.1371/journal.pone.0212216>
- Sale, D. G. (1988). Neural adaptation to resistance training. *Medicine and Science in Sports and Exercise*, *20*(5 Suppl), S135–S145. <https://doi.org/10.1249/00005768-198810001-00009>
- Santaniello, N., Nóbrega, S. R., Scarpelli, M. C., Alvarez, I. F., Otoboni, G. B., Pintanel, L., & Libardi, C. A. (2020). Effect of resistance training to muscle failure vs non-failure on strength, hypertrophy and

muscle architecture in trained individuals. *Biology of Sport*, 37(4), 333–341.

<https://doi.org/10.5114/biol sport.2020.96317>

Santos, P. D. G., Vaz, J. R., Correia, J., Neto, T., & Pezarat-Correia, P. (2023). Long-Term Neurophysiological Adaptations to Strength Training: A Systematic Review With Cross-Sectional Studies. *Journal of Strength and Conditioning Research*, 37(10), 2091–2105.

<https://doi.org/10.1519/JSC.0000000000004543>

Santos, P. D. G., Vaz, J. R., Correia, P. F., Valamatos, M. J., Veloso, A. P., & Pezarat-Correia, P. (2021).

Intermuscular Coordination in the Power Clean Exercise: Comparison between Olympic Weightlifters and Untrained Individuals-A Preliminary Study. *Sensors (Basel, Switzerland)*, 21(5),

1904. <https://doi.org/10.3390/s21051904>

Sbriccoli, P., Bazzucchi, I., Rosponi, A., Bernardi, M., De Vito, G., & Felici, F. (2003). Amplitude and spectral characteristics of biceps Brachii sEMG depend upon speed of isometric force generation.

Journal of Electromyography and Kinesiology, 13(2), 139–147. [https://doi.org/10.1016/S1050-6411\(02\)00098-6](https://doi.org/10.1016/S1050-6411(02)00098-6)

Schober, P., Mascha, E. J., & Vetter, T. R. (2021). Statistics From A (Agreement) to Z (z Score): A Guide to Interpreting Common Measures of Association, Agreement, Diagnostic Accuracy, Effect Size, Heterogeneity, and Reliability in Medical Research. *Anesthesia & Analgesia*, 133(6), 1633–1641.

<https://doi.org/10.1213/ANE.0000000000005773>

Schoenfeld, B. (2016). *Science and development of muscle hypertrophy* [Book]. Human Kinetics.

Schoenfeld, B., Fisher, J., Grgic, J., Haun, C., Helms, E., Phillips, S., Steele, J., & Vigotsky, A. (2021).

Resistance Training Recommendations to Maximize Muscle Hypertrophy in an Athletic Population: Position Stand of the IUSCA. *International Journal of Strength and Conditioning*, 1(1).

<https://doi.org/10.47206/ijsc.v1i1.81>

Schoenfeld, B. J., Grgic, J., Ogborn, D., & Krieger, J. W. (2017). Strength and Hypertrophy Adaptations

Between Low- vs. High-Load Resistance Training: A Systematic Review and Meta-analysis. *Journal*

of Strength and Conditioning Research, 31(12), 3508–3523.

<https://doi.org/10.1519/JSC.0000000000002200>

Semmler, J. G. (2002). Motor Unit Synchronization and Neuromuscular Performance. *Exercise and Sport Sciences Reviews*, 30(1), 8–14. <https://doi.org/10.1097/00003677-200201000-00003>

Sers, R., Forrester, S., Moss, E., Ward, S., Ma, J., & Zecca, M. (2020). Validity of the Perception Neuron inertial motion capture system for upper body motion analysis. *Measurement: Journal of the International Measurement Confederation*, 149, 107024.

<https://doi.org/10.1016/j.measurement.2019.107024>

Shieh, G. (2016). Choosing the best index for the average score intraclass correlation coefficient.

Behavior Research Methods, 48(3), 994–1003. <https://doi.org/10.3758/s13428-015-0623-y>

Siddique, U., Rahman, S., Frazer, A. K., Pearce, A. J., Howatson, G., & Kidgell, D. J. (2020).

Determining the Sites of Neural Adaptations to Resistance Training: A Systematic Review and

Meta-analysis. *Sports Medicine (Auckland)*, 50(6), 1107–1128. <https://doi.org/10.1007/s40279-020-01258-z>

Singla, D., Hussain, M. E., Bhati, P., Moiz, J. A., Ahmad, I., Verma, S., & Ali, K. (2018). Reliability of

Electromyographic Assessment of Biceps Brachii and Triceps Brachii in Cricketers. *Journal of*

Chiropractic Medicine, 17(3), 151–159. <https://doi.org/10.1016/j.jcm.2018.04.001>

Škarabot, J., Brownstein, C. G., Casolo, A., Del Vecchio, A., & Ansdell, P. (2021). The knowns and

unknowns of neural adaptations to resistance training. *European Journal of Applied Physiology*,

121(3), 675–685. <https://doi.org/10.1007/s00421-020-04567-3>

Snarr, R. L., Hallmark, A. V., Casey, J. C., & Esco, M. R. (2017). Electromyographical Comparison of a

Traditional, Suspension Device, and Towel Pull-Up. *Journal of Human Kinetics*, 58(1), 5–13.

<https://doi.org/10.1515/hukin-2017-0068>

- Soderberg, G. L., & Knutson, L. M. (2000). A guide for Use and Interpretation of Kinesiological Electromyographic Data. In *Physical Therapy* (Vol. 80).
<https://academic.oup.com/ptj/article/80/5/485/2842519>
- Solstad, T. E., Andersen, V., Shaw, M., Hoel, E. M., Vonheim, A., & Saeterbakken, A. H. (2020). A Comparison of Muscle Activation between Barbell Bench Press and Dumbbell Flyes in Resistance-Trained Males. *Journal of Sports Science & Medicine*, *19*(4), 645–651.
<http://www.ncbi.nlm.nih.gov/pubmed/33239937>
- Sorbie, G. G., Williams, M. J., Boyle, D. W., Gray, A., Brouner, J., Gibson, N., Baker, J. S., Easton, C., & Ugbohue, U. C. (2018). Intra-session and Inter-day Reliability of the Myon 320 Electromyography System During Sub-maximal Contractions. *Frontiers in Physiology*, *9*(MAR).
<https://doi.org/10.3389/fphys.2018.00309>
- Sousa, A. S. P., Manuel, J., & Tavares, R. S. (2012). *Surface electromyographic amplitude normalization methods: A review* (H. Takada, Ed.; 1st ed.). Nova Science.
<https://www.researchgate.net/publication/286051017>
- Soylu, A. R., Ertan, H., & Korkusuz, F. (2006). Archery performance level and repeatability of event-related EMG. *Human Movement Science*, *25*(6), 767–774.
<https://doi.org/10.1016/j.humov.2006.05.002>
- Spiliopoulou, P., Methenitis, S., Zaras, N., Stasinaki, A.-N., Krekoukia, M., Tsitkanou, S., & Terzis, G. (2022). Vastus Lateralis and Vastus Intermedius as Predictors of Quadriceps Femoris Muscle Hypertrophy after Strength Training. *Applied Sciences*, *12*(18), 9133.
<https://doi.org/10.3390/app12189133>
- Spudić, D., Smajla, D., & Šarabon, N. (2020). Intra-session reliability of electromyographic measurements in flywheel squats. *PLoS ONE*, *15*(12 December).
<https://doi.org/10.1371/journal.pone.0243090>

- Sterczala, A. J., Miller, J. D., Dimmick, H. L., Wray, M. E., Trevino, M. A., & Herda, T. J. (2020). Eight weeks of resistance training increases strength, muscle cross-sectional area and motor unit size, but does not alter firing rates in the vastus lateralis. *European Journal of Applied Physiology*, *120*(1), 281–294. <https://doi.org/10.1007/s00421-019-04273-9>
- Stock, M. S., Beck, T. W., DeFreitas, J. M., & Dillon, M. A. (2010). An examination of the linearity and reliability of the electromyographic amplitude versus dynamic constant external resistance relationships using monopolar and bipolar recording methods. *Journal of Neuroscience Methods*, *194*(1), 94–101. <https://doi.org/10.1016/j.jneumeth.2010.09.014>
- Sy, A. C., & Bugtai, N. T. (2014). Velocity and acceleration induced response to bicep EMG signal threshold for motion intention detection [Proceeding]. *2014 International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)*, 1–6. <https://doi.org/10.1109/HNICEM.2014.7016198>
- Taborri, J., Agostini, V., Artemiadis, P. K., Ghislieri, M., Jacobs, D. A., Roh, J., & Rossi, S. (2018). Feasibility of Muscle Synergy Outcomes in Clinics, Robotics, and Sports: A Systematic Review. *Applied Bionics and Biomechanics*, *2018*, 1–19. <https://doi.org/10.1155/2018/3934698>
- Taborri, J., Keogh, J., Kos, A., Santuz, A., Umek, A., Urbanczyk, C., van der Kruk, E., & Rossi, S. (2020). Sport biomechanics applications using inertial, force, and EMG sensors: A literature overview. *Applied Bionics and Biomechanics*, *2020*. <https://doi.org/10.1155/2020/2041549>
- Taborri, J., Palermo, E., Del Prete, Z., & Rossi, S. (2018). On the Reliability and Repeatability of Surface Electromyography Factorization by Muscle Synergies in Daily Life Activities. *Applied Bionics and Biomechanics*, *2018*, 1–15. <https://doi.org/10.1155/2018/5852307>
- TAX, A. A. M., DENIER VAN DER GON, J. J., & ERKELENS, C. J. (1990). Differences in coordination of elbow flexor muscles in force tasks and in movement tasks. *Experimental Brain Research*, *81*(3), 567–572. <https://doi.org/10.1007/BF02423505>

- Taylor, A. M., Christou, E. A., & Enoka, R. M. (2003). Multiple Features of Motor-Unit Activity Influence Force Fluctuations During Isometric Contractions. *Journal of Neurophysiology*, 90(2), 1350–1361. <https://doi.org/10.1152/jn.00056.2003>
- Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011). No evidence of expertise-related changes in muscle synergies during rowing. *Journal of Electromyography and Kinesiology*, 21(6), 1030–1040. <https://doi.org/10.1016/j.jelekin.2011.07.013>
- Uliam, H., de Azevedo, F. M., Ota Takahashi, L. S., Moraes, E., Negro Filho, R. de F., & Alves, N. (2012). The Relationship Between Electromyography and Muscle Force [Bookitem]. In *EMG Methods for Evaluating Muscle and Nerve Function*. InTech. <https://doi.org/10.5772/25381>
- Uysal, Ö., Akoğlu, A. S., Kara, D., Sezik, A. Ç., Çalik, M., & Düzgün, I. (2022). Theraband Applications for Improved Upper Extremity Wall-Slide Exercises. *Journal of Athletic Training*, 57(8), 795–803. <https://doi.org/10.4085/1062-6050-0305.21>
- Vieira, T. M., Bisi, M. C., Stagni, R., & Botter, A. (2017). Changes in tibialis anterior architecture affect the amplitude of surface electromyograms. *Journal of NeuroEngineering and Rehabilitation*, 14(1). <https://doi.org/10.1186/s12984-017-0291-5>
- Vigotsky, A. D., Halperin, I., Trajano, G. S., & Vieira, T. M. (2022). Longing for a Longitudinal Proxy_ Acutely Measured Surface EMG Amplitude is not a Validated Predictor of Muscle Hypertrophy. *Sports Medicine*, 52(2), 193–199. <https://doi.org/10.1007/s40279-021-01619-2>
- Vítečková, S., Horáková, H., Poláková, K., Krupička, R., Růžička, E., & Brožová, H. (2020). Agreement between the GAITRite® System and the Wearable Sensor BTS G-Walk® for measurement of gait parameters in healthy adults and Parkinson's disease patients. *PeerJ (San Francisco, CA)*, 8, e8835–e8835. <https://doi.org/10.7717/peerj.8835>
- Volkan, M., Çobanoğlu, G., Küpeli, B., Ozkul, C., Oskay, D., & Güzel, N. A. (2020). The reliability of a wearable movement analysis system (G-walk) on gait and jump assessment in healthy adults. *Journal of Exercise Therapy and Rehabilitation*, 7(2), 159–167.

- von Werder, S. C. F. A., & Disselhorst-Klug, C. (2016). The role of biceps brachii and brachioradialis for the control of elbow flexion and extension movements. *Journal of Electromyography and Kinesiology*, 28, 67–75. <https://doi.org/10.1016/j.jelekin.2016.03.004>
- Walker, S. (2021). Evidence of resistance training-induced neural adaptation in older adults. *Experimental Gerontology*, 151, 111408. <https://doi.org/10.1016/j.exger.2021.111408>
- Weir, J. P. (2005). Quantifying Test-Retest Reliability Using the Intraclass Correlation Coefficient and the SEM. *The Journal of Strength and Conditioning Research*, 19(1), 231. <https://doi.org/10.1519/15184.1>
- Wiesinger, H.-P., Kosters, A., Muller, E., & Seynnes, O. R. (2015). Effects of Increased Loading on In Vivo Tendon Properties: A Systematic Review. *Medicine and Science in Sports and Exercise*, 47(9), 1885–1895. <https://doi.org/10.1249/MSS.0000000000000603>
- Wiley, J. (2024, March 26). *Multilevel Models using lmer*. <https://joshuawiley.com/multilevelTools/articles/lmer-vignette.html>
- Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed.) [Book]. Wiley.
- Worrell, T. W., Crisp, E., & LaRosa, C. (1998). Electromyographic Reliability and Analysis of Selected Lower Extremity Muscles During Lateral Step-Up Conditions. *Journal of Athletic Training*, 33(2), 156–162.
- Youdas, J. W., Amundson, C. L., Cicero, K. S., Hahn, J. J., Harezlak, D. T., & Hollman, J. H. (2010). Surface Electromyographic Activation Patterns and Elbow Joint Motion During a Pull-Up, Chin-Up, or Perfect-Pullup™ Rotational Exercise. *Journal of Strength and Conditioning Research*, 24(12), 3404–3414. <https://doi.org/10.1519/JSC.0b013e3181f1598c>
- Young, A. D. (2010). Use of Body Model Constraints to Improve Accuracy of Inertial Motion Capture [Proceeding]. *2010 International Conference on Body Sensor Networks*, 180–186. <https://doi.org/10.1109/BSN.2010.30>

- Yue, G., & Cole, K. J. (1992). Strength increases from the motor program: comparison of training with maximal voluntary and imagined muscle contractions. *Journal of Neurophysiology*, 67(5), 1114–1123. <https://doi.org/10.1152/jn.1992.67.5.1114>
- Zabaleta-Korta, A., Fernández-Peña, E., Torres-Unda, J., Garbisu-Hualde, A., & Santos-Concejero, J. (2021). The role of exercise selection in regional Muscle Hypertrophy: A randomized controlled trial. *Journal of Sports Sciences*, 39(20), 2298–2304. <https://doi.org/10.1080/02640414.2021.1929736>
- Zandi, S., Rajabi, R., Mohseni-Bandpei, M., & Minoonejad, H. (2018). Electromyographic Analysis of Shoulder Girdle Muscles in Volleyball Throw: A Reliability Study. *Biomedical Human Kinetics*, 10(1), 141–149. <https://doi.org/10.1515/bhk-2018-0021>
- Zunner, B. E. M., Wachsmuth, N. B., Eckstein, M. L., Scherl, L., Schierbauer, J. R., Haupt, S., Stumpf, C., Reusch, L., & Moser, O. (2022). Myokines and Resistance Training: A Narrative Review. *International Journal of Molecular Sciences*, 23(7), 3501. <https://doi.org/10.3390/ijms23073501>

Appendix A



Get Active Questionnaire

CANADIAN SOCIETY FOR EXERCISE PHYSIOLOGY –
PHYSICAL ACTIVITY TRAINING FOR HEALTH (CSEP-PATH®)

Physical activity improves your physical and mental health. Even small amounts of physical activity are good, and more is better.

For almost everyone, the benefits of physical activity far outweigh any risks. For some individuals, specific advice from a Qualified Exercise Professional (QEP – has post-secondary education in exercise sciences and an advanced certification in the area – see csep.ca/certifications) or health care provider is advisable. This questionnaire is intended for all ages – to help move you along the path to becoming more physically active.

- I am completing this questionnaire for myself.
- I am completing this questionnaire for my child/dependent as parent/guardian.

YES	NO	PREPARE TO BECOME MORE ACTIVE
		The following questions will help to ensure that you have a safe physical activity experience. Please answer YES or NO to each question <u>before</u> you become more physically active. If you are unsure about any question, answer YES .
		1 Have you experienced ANY of the following (A to F) within the past six months ?
		A A diagnosis of/treatment for heart disease or stroke, or pain/discomfort/pressure in your chest during activities of daily living or during physical activity?
		B A diagnosis of/treatment for high blood pressure (BP), or a resting BP of 160/90 mmHg or higher?
		C Dizziness or lightheadedness during physical activity?
		D Shortness of breath at rest?
		E Loss of consciousness/fainting for any reason?
		F Concussion?
		2 Do you currently have pain or swelling in any part of your body (such as from an injury, acute flare-up of arthritis, or back pain) that affects your ability to be physically active?
		3 Has a health care provider told you that you should avoid or modify certain types of physical activity?
		4 Do you have any other medical or physical condition (such as diabetes, cancer, osteoporosis, asthma, spinal cord injury) that may affect your ability to be physically active?
	 > NO to all questions: go to Page 2 – ASSESS YOUR CURRENT PHYSICAL ACTIVITY
		YES to any question: go to Reference Document – ADVICE ON WHAT TO DO IF YOU HAVE A YES RESPONSE >>>

ASSESS YOUR CURRENT PHYSICAL ACTIVITY

Answer the following questions to assess how active you are now.

- 1 During a typical week, on how many days do you do moderate- to vigorous-intensity aerobic physical activity (such as brisk walking, cycling or jogging)? DAYS/
WEEK
 - 2 On days that you do at least moderate-intensity aerobic physical activity (e.g., brisk walking), for how many minutes do you do this activity? MINUTES/
DAY
- For adults, please multiply your average number of days/week by the average number of minutes/day: MINUTES/
WEEK

Canadian 24-Hour Movement Guidelines recommend that adults accumulate at least 150 minutes of moderate- to vigorous-intensity physical activity per week. For children and youth, at least 60 minutes daily is recommended. Strengthening muscles and bones at least two times per week for adults, and three times per week for children and youth, is also recommended (see csep.ca/guidelines).

GENERAL ADVICE FOR BECOMING MORE ACTIVE

Increase your physical activity gradually so that you have a positive experience. Build physical activities that you enjoy into your day (e.g., take a walk with a friend, ride your bike to school or work) and reduce your sedentary behaviour (e.g., prolonged sitting).

If you want to do **vigorous-intensity physical activity** (i.e., physical activity at an intensity that makes it hard to carry on a conversation), and you do not meet minimum physical activity recommendations noted above, consult a Qualified Exercise Professional (QEP) beforehand. This can help ensure that your physical activity is safe and suitable for your circumstances.

Physical activity is also an important part of a healthy pregnancy.

Delay becoming more active if you are not feeling well because of a temporary illness.

DECLARATION

To the best of my knowledge, all of the information I have supplied on this questionnaire is correct.
If my health changes, I will complete this questionnaire again.

I answered **NO** to all questions on Page 1

I answered **YES** to any question on Page 1

Sign and date the Declaration below

Check the box below that applies to you:

- I have consulted a health care provider or Qualified Exercise Professional (QEP) who has recommended that I become more physically active.
- I am comfortable with becoming more physically active on my own without consulting a health care provider or QEP.

<input type="text"/>	<input type="text"/>	<input type="text"/>
Name (+ Name of Parent/Guardian if applicable) [Please print]	Signature (or Signature of Parent/Guardian if applicable)	Date of Birth
<input type="text"/>	<input type="text"/>	<input type="text"/>
Date	Email (optional)	Telephone (optional)

With planning and support you can enjoy the benefits of becoming more physically active. A QEP can help.

- Check this box if you would like to consult a QEP about becoming more physically active.
(This completed questionnaire will help the QEP get to know you and understand your needs.)

Appendix B



Université d'Ottawa
Faculté des sciences
de la santé

École des sciences de
l'activité physique

University of Ottawa
Faculty of Health
Sciences

School of Human
Kinetics

☎ 613-562-5853
☎ 613-562-5149

125 University Private
Ottawa ON K1N 6N5 Canada
www.uOttawa.ca

Research Consent Form

Research Project Title: Assessing Inter-Day Reliability of Surface EMG Amplitude for Resistance Training Exercise Selection.

Principal Investigator: Mike Croskery¹
Supervisor: Dr. Ryan Graham¹ (613-562-5800 X 1025;
ryan.graham@uottawa.ca)

¹University of Ottawa, Faculty of Health Sciences, Department of Human Kinetics, 200 Lees Ave, Ottawa, ON K1N6N5

Health Precautions:

For the safety of both you and the researcher, precautions have been put in place to try and prevent the spread of COVID-19 and other illnesses. Before arriving at the location of choice, the researcher will be screened for COVID-19 symptoms and use hand sanitizer upon entering. The researcher will always wear a mask during the data collection. All equipment a participant or researcher touched during the data collection will be wiped down with disinfectant before and after.

Background and Purpose of the Study:

Exercise selection is an essential component in developing an exercise routine that is correctly matched to an individual's goals. One way to ensure the exercise is appropriate for the desired result is to measure the involved muscles in the exercise movement with surface electromyography (SEMG). SEMG detects the electrical activity within the muscle from the skin's surface during contraction. This electrical activity is believed to be related to the strength of the contraction or "how hard the muscle is working" during the exercise. Thus, if a muscle has a higher level of measured electrical activity, it is thought to have a higher level of tension, which can be desirable for increasing strength and muscle size. Various exercises can challenge the same muscle differently, resulting in different muscle excitation levels or SEMG amplitude. Exercise professionals often look at the different levels of SEMG amplitudes from other exercises for the same muscle (for example, the biceps in various arm curl exercises or the quadriceps muscle across multiple leg exercises) and rank them from most to least effective. However, SEMG amplitudes can vary from day to day depending on various factors specific to the individual, sensor placement, and how the exercise is performed.

The objective of this study is to evaluate if the surface EMG amplitude of the biceps brachii during four unilateral resistance training exercises (unilateral supinated grip dumbbell curl, unilateral neutral grip hammer curl, unilateral supinated grip incline curl, and unilateral supinated grip concentration curl) measured over four different days is repeatable and reliable enough to use for exercise prescription and future research. Muscle excitation will be calculated from four muscles located on your dominant arm using small SEMG sensors

along with an inertial measurement unit (IMU) (about the size of half a pack of playing cards) on your wrist to detect movement angles during seven repetitions of four different arm curl exercises over four other sessions separated by four days (plus or minus one day).

Description of Study Procedures:

You are invited to participate in a study of muscle activation reliability for the biceps brachii (muscle on the front of your upper arm) during four different arm curl exercises that take place at a location of your choice over five separate sessions separated by four days (plus or minus one day to allow for convenient scheduling). Each session will take approximately 1 hour and require moderate to maximal exertion. The first session consists of a practice session to learn the proper exercise technique and to measure the maximal strength of your biceps muscle by measuring how much force you can produce while seated with your elbow bent and stationary at 90 degrees so that your forearm is parallel to the ground. This measurement will determine how much weight you will be lifting for the exercises, so the weight is approximately one-third the force you produce.

During the second, third, fourth and fifth sessions, you will be asked to perform the four arm curl exercises with the selected weight for seven repetitions to the sound of a metronome set at one beat per second so that each full repetition takes four seconds to complete. Specifically, you will be asked to lift the weight at a consistent pace. For example, you reach the top of the motion in 2 seconds. With no pause at the top, you lower the weight at the same consistent pace so that your hand is back at the starting position in 2 seconds. After a 2-second pause, you will repeat the motion for a total of 7 times. Once completed and after a 5-minute rest, you will perform the following exercise at the same tempo for the same number of repetitions. This same protocol will be repeated for the remaining two exercises, so you have completed four arm curl exercises at the end. The sequence in which you will perform these exercises will be randomized for each collection day. You will also be recorded by video that is time synchronized to the EMG sensors and IMU only during the exercises' performance to determine the start and stop of each repetition.

You will be asked to wear a shirt that you are comfortable in to perform exercises that will allow easy access to your upper arm and shoulder on your dominant side, such as a t-shirt or tank top. Upon arrival, you will complete a questionnaire asking you to rate your level of muscle soreness in your upper arm and your general energy level or fatigue. Afterwards, your skin will be prepared for the placement of the EMG sensors by lightly rubbing your skin with an abrasive skin preparation (like hand cleaner or standard facial scrub lotion) and then cleaned with an alcohol swab. Two adhesive electrodes attached to the wireless sensor will be placed on the biceps brachii muscle (midpoint of the front of the upper arm), brachioradialis (upper portion of the top of your forearm), anterior deltoid (front portion of the shoulder) and triceps brachii (midpoint of the back of the upper arm) after marking the location with a semi-permanent surgical marker. In addition, an IMU will be secured to the back of your wrist using medical-grade adhesive and then wrapped in a self-adherent elastic bandage to monitor arm motion during the exercise.

After completing the four exercises, as previously described, the EMG signals will be normalized by performing three maximal voluntary contractions separated by adequate rest for the four involved muscles. Two maximal isometric voluntary contractions (MVIC) (attempted flexion and extension) are performed with the elbow bent at 90 degrees with the palm facing up and down, respectively, and one MVIC in the same position with the palm facing down. The last MVIC is shoulder flexion with the hand in a neutral thumbs-up position. You will be asked to contract your muscles in these four positions against manual resistance for approximately 5 seconds for three times. After the maximal contractions, an outline of the electrodes will be

drawn on your skin using a semi-permanent marker to be able to place the electrodes in the same place for the following session. This purple-inked marker is designed to stay visible on your skin for up to 5 days under everyday hygiene practices. You will be provided with a pen to touch up the markings in case they begin to fade earlier than this.

As your participation in this study is voluntary, at any time during this study, you may withdraw your participation with no consequence. You are encouraged to ask any questions about your involvement during this time. All data collection sessions will be supervised by a certified clinical exercise physiologist with over 25 years of experience in strength and conditioning.

Possible Risks and Discomforts:

You will be performing the arm curl exercises at a submaximal intensity. At this level of exertion, you will feel mild to moderate tension on the biceps muscle, and you could most likely perform 15 to 20 repetitions to fatigue. However, in this case, you must only complete 7 with adequate rest between exercises. Maximal voluntary contractions for the normalization and maximal force production will require a very high, or maximal, intensity to determine the highest possible EMG amplitude or force your muscles can generate for 3 to 5 seconds. This high intensity may be uncomfortable for some, and you may experience temporary discomfort and fatigue during or immediately after.

Any risks will be minimized by completing a health questionnaire (GET ACTIVE) to screen for possible contraindications to performing the necessary tasks. You may also reduce risk by stopping at any time or for any reason during the data collection by simply saying, "I wish to stop," or something like that. As with any exercise participation, there is a risk of muscle strain, fatigue, and muscle soreness from performing these movements. Muscle soreness and fatigue will be monitored for each data collection session. Exercise technique and maximal assessments will be assessed by a qualified clinical exercise physiologist with more than 25 years of experience in strength testing and prescription to ensure proper execution and safety. The electrode preparation process may also cause minor skin irritation from the abrasion, alcohol wipe, possible shaving to remove local hair, and the adhesive used to attach the electrodes and the IMU to your skin. Any irritation should be temporary and should fade within 2 to 3 days. Should you experience significant discomfort, please tell us immediately and seek primary care from a medical professional on campus (100 Marie Curie, Ottawa, Tel.: 613-564-3950) or a medical professional.

Possible Benefits:

You will not obtain any direct benefits from participating in this study other than a) performing resistance training exercises for the arm flexor muscle for four sessions and b) obtaining information that may help in determining which arm curl exercise results in the most significant EMG amplitude of the biceps brachii muscle. However, the data collected will help determine if this exercise selection method is reliable in ranking exercise effectiveness based on EMG amplitude for performance, rehabilitation, and general fitness training routines.

Voluntary Participation:

Participation in this study is voluntary, and you are not obligated to participate. You may withdraw from the study before or during the data collection session without penalty or coercion and at any time. There are no social obligations to participate in this study, nor will there be any social or other penalty preventing you from withdrawing from the study at any point. If you choose to participate no longer, all your data will be destroyed.

Confidentiality:

All personal information is kept confidential. Data acquired from this study will be stored electronically and accessible only by a password known only to Mike Croskery. Paper study

records are stored in a locked cabinet and destroyed five years after publication; electronic records will be deleted, and paper records will be incinerated. You will not be identified by name in any completed study reports. Your anonymity will be strictly maintained. Your name will not identify you or be linked to the data collected but instead will be determined by an independent study number (i.e. S01).

Compensation:

Participants in this study will receive a \$50 gift card to their chosen business after completing the five sessions. Note: companies that primarily sell alcohol, cannabis, gambling implements (i.e., lottery tickets, scratch tickets), or other substances at the discretion of the University of Ottawa research team are excluded. Should you decide to leave the study before all sessions are completed, you will receive compensation in the form of a pro-rated gift card at \$10 per session. For example, if you withdraw after completing three sessions, you will receive a gift card to a business of your choice for \$30.

Questions about the Study:

You can ask questions anytime during and after the protocol and by contacting the principal investigator by email or phone. The University of Ottawa Research Ethics Board has approved the ethical components of this research project. Should you have any questions regarding the ethical conduct of this study, you may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa ON, K1N 6N5. Tel.: (613) 562-5387 Email: ethics@uottawa.ca. There are two copies of the consent form, one of which is yours to keep.

Research Project Title: **Assessing Inter-Day Reliability of Surface Emg Amplitude For Resistance Training Exercise Selection**

I have read this consent form, and I agree to participate in the procedures of this study.

Printed Name of Participant

Signature of Participant

Date

Investigator Statement (or Person Explaining the Consent):

I have carefully explained to the research participant the nature of the above research study. To the best of my knowledge, the research participant signing this consent form understands the nature, demands, risks and benefits involved in participating in this study. I acknowledge my responsibility for the care and well-being of the above research participant, to respect the rights and wishes of the research participant, and to conduct the study according to applicable Good Clinical Practice guidelines and regulations.

Name of Investigator/Delegate (printed)

Signature of Investigator/Delegate

Date

Informed Consent to have Pictures and Videos Taken:

I consent to have video taken of myself completing the experiment, and understand that no pictures or video will be taken at any point without me knowing. I also understand that if any of these pictures are used in a subsequent presentation or publication, that my face and any other identifiers will be blurred. Video recordings will be used to verify your start and stop times during the repetitive movements. No videos of yourself will be used for presentations or publication and photographs will be anonymized by obscuring any facial or other identifiable characteristics. You cannot participate in the research study without consenting to have pictures and videos taken.

Name

Date

Signature

Witness Name

Witness Signature

Future Participation:

- I am interested in being contacted to participate in future research performed by this investigator (your contact information will be saved in a password protected file).

Appendix C

06/12/2023

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

CERTIFICAT D'APPROBATION ÉTHIQUE | CERTIFICATE OF ETHICS APPROVAL

Numéro du dossier / Ethics File Number	H-11-23-9781
Titre du projet / Project Title	ASSESSING INTER-DAY RELIABILITY OF SURFACE EMG AMPLITUDE FOR RESISTANCE TRAINING EXERCISE SELECTION.
Type de projet / Project Type	Thèse de maîtrise / Master's thesis
Statut du projet / Project Status	Approuvé / Approved
Date d'approbation (jj/mm/aaaa) / Approval Date (dd/mm/yyyy)	06/12/2023
Date d'expiration (jj/mm/aaaa) / Expiry Date (dd/mm/yyyy)	05/12/2024

Équipe de recherche / Research Team

Chercheur / Researcher	Affiliation	Role
Mike CROSKERY	École des sciences de l'activité physique / School of Human Kinetics	Chercheur Principal / Principal Investigator
Ryan GRAHAM	École des sciences de l'activité physique / School of Human Kinetics	Superviseur / Supervisor

Conditions spéciales ou commentaires / Special conditions or comments

550, rue Cumberland, pièce 154 550 Cumberland Street, Room 154
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada

613-562-5387 • 613-562-5338 • ethique@uOttawa.ca / ethics@uOttawa.ca
www.recherche.uottawa.ca/deontologie | www.recherche.uottawa.ca/ethics

Université d'Ottawa

Bureau d'éthique et d'intégrité de la recherche

University of Ottawa

Office of Research Ethics and Integrity

Le Comité d'éthique de la recherche (CÉR) de l'Université d'Ottawa, opérant conformément à l'*Énoncé de politique des Trois conseils* (2014) et toutes autres lois et tous règlements applicables, a examiné et approuvé la demande d'éthique du projet de recherche ci-nommé.

L'approbation est valide pour la durée indiquée plus haut et est sujette aux conditions énumérées dans la section intitulée "Conditions Spéciales ou Commentaires". Le formulaire « Renouvellement ou Fermeture de Projet » doit être complété quatre semaines avant la date d'échéance indiquée ci-haut afin de demander un renouvellement de cette approbation éthique ou afin de fermer le dossier.

Toutes modifications apportées au projet doivent être approuvées par le CÉR avant leur mise en place, sauf si le participant doit être retiré en raison d'un danger immédiat ou s'il s'agit d'un changement ayant trait à des éléments administratifs ou logistiques du projet. Les chercheurs doivent aviser le CÉR dans les plus brefs délais de tout changement pouvant augmenter le niveau de risque aux participants ou pouvant affecter considérablement le déroulement du projet, rapporter tout événement imprévu ou indésirable et soumettre toute nouvelle information pouvant nuire à la conduite du projet ou à la sécurité des participants.

The University of Ottawa Research Ethics Board, which operates in accordance with the *Tri-Council Policy Statement* (2014) and other applicable laws and regulations, has examined and approved the ethics application for the above-named research project.

Ethics approval is valid for the period indicated above and is subject to the conditions listed in the section entitled "Special Conditions or Comments". The "Renewal/Project Closure" form must be completed four weeks before the above-referenced expiry date to request a renewal of this ethics approval or closure of the file.

Any changes made to the project must be approved by the REB before being implemented, except when necessary to remove participants from immediate endangerment or when the modification(s) only pertain to administrative or logistical components of the project. Investigators must also promptly alert the REB of any changes that increase the risk to participant(s), any changes that considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project or the safety of the participant(s).

Riana MARCOTTE

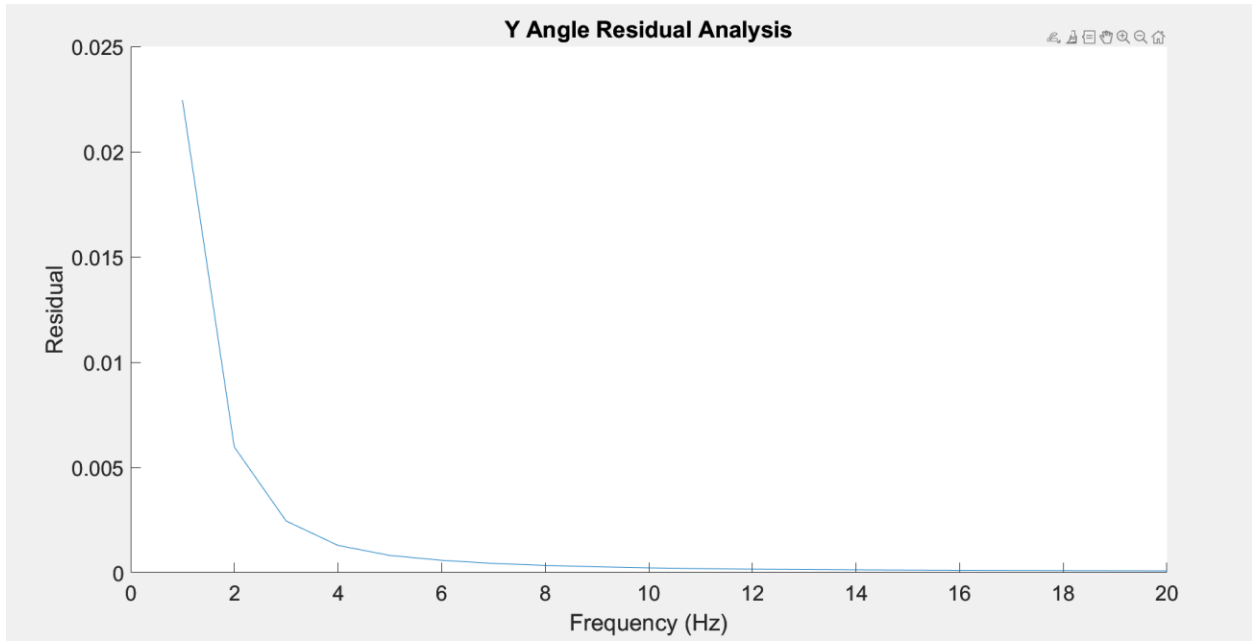
Responsable d'éthique en recherche / Protocol Officer

Pour/For Daniel LAGAREC Président(e) du/ Chair of the Comité d'éthique de la recherche en sciences de la santé et sciences / Health Sciences and Sciences Research Ethics Board

550, rue Cumberland, pièce 154 550 Cumberland Street, Room 154
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada

613-562-5387 • 613-562-5338 • ethique@uOttawa.ca / ethics@uOttawa.ca
www.recherche.uottawa.ca/deontologie | www.recherche.uottawa.ca/ethics

Appendix D

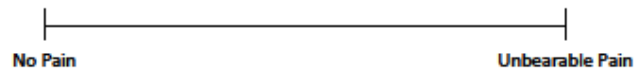


Appendix E

Muscle Soreness Questionnaire

Visual Analog Scale of Muscle Soreness (Cleather & Guthrie, 2007)

- Please draw a vertical line on the scale below that best represents your current intensity of muscle soreness.



Visual Analog Scale For Fatigue (adapted from Lee et al., 1991)

- Please draw a vertical line on the scale below that best represents your current level of fatigue.

