

Kinematics, kinetics, and electromyography of vertical and horizontal hip extension exercises and their transference to acceleration and power

Bret Michael Contreras

A thesis submitted to
Auckland University of Technology
in fulfilment of the degree

DOCTOR OF PHILOSOPHY

2015

Primary Supervisor: Dr. John Cronin
Secondary Supervisor: Dr. Brad Schoenfeld
Sport Performance Research Institute of New Zealand
AUT University, Auckland, New Zealand

TABLE OF CONTENTS

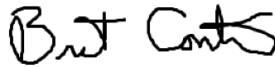
ATTESTATION OF AUTHORSHIP	V
ACKNOWLEDGEMENTS	VI
LIST OF CO-AUTHORED PUBLICATIONS	VII
LIST OF FIGURES	X
LIST OF TABLES	XII
ABSTRACT	XIV
CHAPTER 1	16
PREFACE	16
1.1 Rationale and Significance of Research	17
1.2 Purpose of Research	20
1.3 Significance of Thesis	20
1.4 Structure of Thesis	22
CHAPTER 2	24
A REVIEW OF GLUTEUS MAXIMUS EMG ACTIVITY DURING RESISTED HIP EXTENSION EXERCISE	24
2.0 Lead Summary	25
2.1 Introduction	25
2.2 Search Strategy	28
2.3 Squat Studies	29
2.4 Deadlift Studies	32
2.5 Single Limb Squat Studies	34
2.6 Other Resisted Hip Extension Studies	35
2.7 Leg Press Studies	38
2.8 Kettlebell Studies	39
2.9 Strongman Studies	40
2.10 Limitations	41
2.11 Practical Applications and Conclusion	43
CHAPTER 3	47
3.0 Prelude	47
3.1 BARBELL HIP THRUST TECHNIQUE	48
3.1.1 Summary	49
3.1.2 Type of Exercise	49
3.1.3 Muscles Used and Benefits	49
3.1.4 Exercise Technique	50
3.1.5 Set Strategies	55
3.1.6 Sets/Repetitions/Rest	56
3.1.7 Load	57
3.2 ARE ALL HIP EXTENSION EXERCISES CREATED EQUAL?	58
3.2.0 Summary	59
3.2.1 Introduction	60
3.2.2 Biomechanical Analysis of Selected Hip Extension Exercises	61
3.2.3 Practical Applications	65
3.2.4 Conclusion	71
CHAPTER 4	73
A COMPARISON OF TWO GLUTEUS MAXIMUS EMG MAXIMUM VOLUNTARY ISOMETRIC CONTRACTION POSITIONS	73
4.0 Prelude	74
4.1 Introduction	74
4.2 Methods	77
4.3 Results	80

4.4 Discussion	81
4.5 Conclusion	84
CHAPTER 5	85
A COMPARISON OF GLUTEUS MAXIMUS, BICEPS FEMORIS, AND VASTUS LATERALIS EMG ACTIVITY IN THE PARALLEL, FULL, AND FRONT SQUAT VARIATIONS	85
5.0 Prelude	86
5.1 Introduction	86
5.2 Methods	90
5.3 Results	96
5.4 Discussion	97
CHAPTER 6	102
A COMPARISON OF GLUTEUS MAXIMUS, BICEPS FEMORIS, AND VASTUS LATERALIS EMG ACTIVITY IN THE BARBELL, BANDED, AND AMERICAN HIP THRUST VARIATIONS	102
6.0 Prelude	103
6.1 Introduction	103
6.2 Methods	106
6.3 Results	112
6.4 Discussion	113
CHAPTER 7	118
A COMPARISON OF GLUTEUS MAXIMUS, BICEPS FEMORIS, AND VASTUS LATERALIS EMG ACTIVITY IN THE BACK SQUAT AND BARBELL HIP THRUST EXERCISES	118
7.0 Prelude	119
7.1 Introduction	119
7.2 Methods	121
7.3 Results	127
7.4 Discussion	128
CHAPTER 8	135
KINETIC ANALYSIS OF THE BACK SQUAT AND BARBELL HIP THRUST EXERCISES	135
8.0 Prelude	136
8.1 Introduction	136
8.2 Methods	139
8.3 Results	142
8.4 Discussion	142
8.5 Practical Applications	145
CHAPTER 9	146
EFFECTS OF A SIX-WEEK SQUAT VERSUS HIP THRUST PROGRAM ON PERFORMANCE	146
9.0 Prelude	147
9.1 Introduction	147
9.2 Methods	151
9.3 Results	156
9.4 Discussion	159
9.5 Practical Applications	164
CHAPTER 10	166
RELIABILITY OF THE MAXIMUM HORIZONTAL PUSH FORCE TEST	166
10.0 Prelude	167
10.1 Introduction	167
10.2 Methods	169
10.3 Results	172
10.4 Discussion	172
10.5 Practical Applications	173

CHAPTER 11	175
EFFECTS OF A SIX-WEEK SQUAT VERSUS HIP THRUST PROGRAM ON GLUTEUS MAXIMUS THICKNESS AND HORIZONTAL FORCE PRODUCTION IN MONOZYGOTIC TWINS: A SINGLE-SUBJECT DESIGN	175
11.0 Prelude	176
11.1 Introduction	176
11.2 Methods	178
11.3 Results	182
11.4 Discussion	185
11.5 Practical Applications	188
 CHAPTER 12	 189
SUMMARY, PRACTICAL APPLICATIONS AND FUTURE RESEARCH DIRECTIONS	189
12.1 General Summary	190
12.2 Limitations	193
12.3 Practical Applications	197
12.4 Future Research Directions	200
 REFERENCES	 203
 APPENDICES	 225
Appendix 1. Ethics Approval Forms	225
Appendix 1a. Ethics Application Number 13/375	225
Appendix 1b. Ethics Application Number 14/267	226
Appendix 2. Consent Forms	227
Appendix 2a. Electromyographical Activity of Various Hip Extension Exercises	227
Appendix 2b. Kinematic, Kinetic and Morphological Adaptations to Training with Various Hip Extension Exercises	229
Appendix 2c. Kinematic, Kinetic and Morphological Adaptations to Training With Various Hip Extension Exercises	231
Appendix 3. Study Information Sheets	232
Appendix 3a. Electromyographical Activity of Various Hip Extension Exercises	232
Appendix 3b. Kinematic, Kinetic and Morphological Adaptations to Training with Various Hip Extension Exercises	235
Appendix 4. Abstracts of Chapters as Published, In Press, or In Review	238
Appendix 4a. Chapter 2: Strength & Conditioning Journal	238
Abstract	238
Appendix 4b. Chapter 3.1: Strength & Conditioning Journal	239
Appendix 4c. Chapter 3.2: Strength & Conditioning Journal	240
Appendix 4d. Chapter 4: PeerJ	241
Appendix 4e. Chapter 5: Journal of Applied Biomechanics	242
Appendix 4f. Chapter 7: Journal of Applied Biomechanics	243
Appendix 4g. Chapter 7: Journal of Applied Biomechanics	244
Appendix 4h. Chapter 8: Journal of Applied Biomechanics	245
Appendix 4i. Chapter 9: Journal of Strength & Conditioning Research	246
Appendix 4j. Chapter 10: Sports Biomechanics	247
Appendix 4k. Chapter 11: Journal of Strength & Conditioning Research	248
Appendix 5. Electromyography	249

ATTESTATION OF AUTHORSHIP

"I hereby declare that this thesis submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

A handwritten signature in black ink, appearing to read "Bret Contreras". The signature is stylized with a large, looped 'B' and a cursive 'Contreras'.

Bret Michael Contreras

ACKNOWLEDGEMENTS

I would first like to acknowledge my grandfather, Edward Burdick, an engineer by trade. He saw to it that I was exposed to plenty of science at a young age, which ignited a fire that would stay lit for life. Thanks, Gramps, for the subscriptions to *Discover Magazine*, for all the Physics and Mathematics texts you consistently provided over the years from the likes of Stephen Hawking, Richard Feynman, and Albert Einstein, and for helping me out financially whenever it pertained to my education. I only wish that you were still around to see me defend my thesis and earn the PhD title; I know you would have been proud of your grandson.

I would like to offer my sincerest thanks and praise to my primary supervisor John Cronin. If it weren't for John, I wouldn't have stuck it out and completed my PhD. People like John make the world a better place. John has served as a mentor and a teacher, but also like a second father. Being under his guidance has made me strive to do more. The passion and commitment he puts into his students is undeserved but immensely appreciated. Thank you John, for believing in me and for taking me on as a PhD student in the first place.

A big thanks also goes out to my good friend Brad Schoenfeld. There were two different times when I considered quitting my PhD and Brad wouldn't hear of it. He encouraged me to see it through, and now that I'm done with the thesis, I'm so glad that I listened to him and took his advice. Brad's wisdom was invaluable and I can't thank him enough for his support.

I'd like to thank my friend Chris Beardsley for inspiring me and raising the bar. Chris is the most competent person I know, and having him as a colleague motivated me to conduct the highest quality research possible and see the thesis through.

Finally, I'd like to give the utmost praise to my former intern Andrew Vigotsky. Although currently only 23 years old, Andrew's intelligence is beyond measure, and he will undoubtedly go on to do great things in the field of sports science. Thank you to Andrew for his insight and for countless hours spent discussing the thesis.

LIST OF CO-AUTHORED PUBLICATIONS

The contribution of co-authors for publications (e.g., Contreras 85%) arising from these research studies and from whom approval has been granted below for inclusion in this doctoral thesis.

Published/Accepted

Contreras, B., Cronin, J., & Schoenfeld, B. (2011). Barbell hip thrust. *Strength & Conditioning Journal*, 33(5), 58-61.

(Contreras 90%, Cronin 5%, Schoenfeld 5%)

Contreras, B. M., Cronin, J. B., Schoenfeld, B. J., Nates, R. J., & Sonmez, G. T. (2013). Are all hip extension exercises created equal?. *Strength & Conditioning Journal*, 35(2), 17-22.

(Contreras 87.5%, Cronin 5%, Schoenfeld 2.5%, Nates 2.5%, Sonmez 2.5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A. Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis Electromyography Amplitude in the Parallel, Full, and Front Squat Variations in Resistance-Trained Females. *Journal of Applied Biomechanics*, 32(1), 16-22.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A. A comparison of gluteus maximus, biceps femoris, and vastus lateralis EMG activity in the back squat and barbell hip thrust exercises. *Journal of Applied Biomechanics*, In Press March 11, 2016.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

Contreras, B., Vigotsky, A., Schoenfeld, B., Cronin, J. A. A comparison of two gluteus maximus EMG maximum voluntary isometric contraction positions. *PeerJ*, 3, e1261.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis EMG Amplitude for the Barbell, Band, and American Hip Thrust Variations. *Journal of Applied Biomechanics*. In Press March 11, 2016.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

Under Review

Contreras, B., Vigotsky, A., Schoenfeld, B., & Cronin, J. A review of gluteus maximus EMG activity during resisted hip extension exercise. *Strength & Conditioning Journal*, In review March 11, 2016.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A kinetic analysis of the back squat and barbell hip thrust exercises. *Journal of Applied Biomechanics*, In review March 11, 2016.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., Schuster, J., & Cronin, J. Reliability of the maximum horizontal push test. *Sports Biomechanics*. In review March 11, 2016.

(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Schuster 2.5%, Cronin 2.5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., Reyneke J., McMasters T., & Cronin, J. Effects of a six-week squat versus hip thrust program on performance. *Journal of Strength & Conditioning Research*, In review March 11, 2016.

(Contreras 85%, Vigotsky 2.5%, Schoenfeld 2.5%, Beardsley 2.5%, Reyneke 2.5%, McMasters 2.5%, Cronin 2.5%)

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. Effects of a six-week squat versus hip thrust program on gluteus maximus thickness and horizontal force production in monozygotic twins: a single-subject design. *Journal of Strength & Conditioning Research*, In review March 11, 2016.

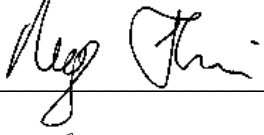
(Contreras 85%, Vigotsky 5%, Schoenfeld 2.5%, Beardsley 2.5%, Cronin 5%)

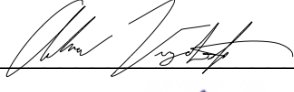
Conference Presentations

N/A

Doctoral Candidate: Bret Michael Contreras 

Primary Supervisor: Dr. John Cronin 


Associate Supervisor: Dr. Nigel Harris 


Contributor: Andrew Vigotsky 

Contributor: Chris Beardsley 

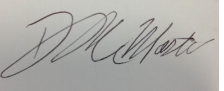
Contributor: Dr. Brad Schoenfeld 

Contributor: Dr. Gul Tiryaki Sonmez 

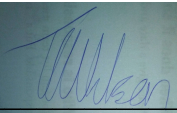
Contributor: Dr. Roy Nates 

Contributor: Jake Schuster 

Contributor: Jan Reyneke 

Contributor: Dr. Travis McMasters 

Contributor: Dr. Craig Harrison 

Contributor: Timothy Wilson 

LIST OF FIGURES

Figure 3.1.1 How to begin the setup of the hip thrust.

Figure 3.1.2 Demonstration of how to grab the barbell.

Figure 3.1.3 The bar is to be pulled over the thighs, toward the hips.

Figure 3.1.4 Flex the knees to 90°.

Figure 3.1.5 Brace for the lift.

Figure 3.1.6 Extend the hips, thrusting the bar upward.

Figure 3.2.1 90, 135, and 180° of hip extension in the good morning, 45° back extension, and horizontal back extension exercises.

Figure 3.2.2 Sample calculation for 45° back extension exercise at a hip position of 135°.

Figure 3.2.3 Graph of instantaneous hip torque at selected ranges of motion in three different hip extension exercises.

Figure 4.1 Prone bent-leg hip extension against manual resistance maximum voluntary isometric contraction position.

Figure 4.2 Standing glute squeeze maximum voluntary isometric contraction position.

Figure 4.3 Group mean \pm SD of normalized peak EMG amplitudes.

Figure 5.1 Front squat form.

Figure 5.2 Full squat form.

Figure 5.3 Parallel squat form.

Figure 6.1 Barbell hip thrust form.

Figure 6.2 American hip thrust form.

Figure 6.3 Band hip thrust form.

Figure 7.1 Back squat form.

Figure 7.2 Hip thrust form.

Figure 8.1 Performance of the hip thrust (left) and parallel squat (right) on the force plate.

Figure 9.1 Within-group effect sizes (\pm 95% CL) following six weeks of hip thrusting.

Figure 9.2 Within-group effect sizes (\pm 95% CL) following six weeks of front squatting.

Figure 9.3 Between-group effect sizes (\pm 95% CL) of performance measures.

Figure 10.1 Form of the maximum horizontal push test. The body is 45° with the ground and arms are extended and parallel with the ground.

Figure 11.1 Volume load (kg) in the squat and hip thrust across all six weeks.

Figure 11.2 Changes in gluteus maximus thickness (cm).

Figure 11.3 Changes in maximum horizontal pushing force (MHPF).

LIST OF TABLES

Table 2.1 Resisted squat exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 2.2 Resisted deadlift exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 2.3 Resisted single limb squat exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 2.4 Resisted hip extension exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 2.5 Resisted leg press exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 2.6 Resisted kettlebell exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 2.7 Resisted strongman exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Table 3.2.1 Instantaneous hip extension torque at selected ranges in three different straight leg hip extension exercises.

Table 4.1 Group mean \pm SD of normalized peak EMG amplitudes.

Table 4.2 Number of subjects (percentage of subjects (%)) to achieve maximal activation in each MVIC technique.

Table 5.1 Mean \pm SD of EMG (%MVIC) values in the parallel, full, and front squat.

Table 6.1 Mean \pm SD of EMG (%MVIC) values in the barbell, band, and American hip thrusts.

Table 6.2 Number of subjects (% of subjects) to achieve maximal activation in each exercise.

Table 7.1 Mean (\pm SD) and peak EMG amplitudes (% MVIC) of the upper gluteus maximus, lower gluteus maximus, biceps femoris, and vastus lateralis during the barbell hip thrust and back squat.

Table 7.2 EMG findings of previous research on the back squat for the gluteus maximus, biceps femoris, and vastus lateralis muscles compared to current findings.

Table 8.1 Comparison between the vertical kinetics of the back squat and hip thrust.

Table 9.1 Comparison of baseline characteristics of the squat and hip thrust groups.

Table 9.2 Sets and repetition schemes utilized for the squat and hip thrust.

Table 9.3 Pre- and post- measures, differences, and percent change of all performance measures.

Table 10.1 Reliability of peak horizontal force for the maximum horizontal push test.

Table 11.1 Training protocol.

Table 11.2 Changes in gluteus maximus thickness (cm).

Table 11.3 Changes in strength measures.

Table 12.1 Advantages of squats versus hip thrusts.

ABSTRACT

The squat is a very popular exercise in resistance training, utilized by populations ranging from clinical to elite athletes. A myriad of literature has shown that squats are effective for improving strength, performance, and hypertrophy. Due to the inherent nature of the squat, it is loaded vertically, or axially. The hip thrust, however, is a new, horizontally-, or anteroposteriorly-loaded exercise utilized to work the hip extensors, especially at end-range hip extension. The nature of the hip thrust makes it especially useful for achieving maximal gluteus maximus activation, as maximal activation is elicited at end-range hip extension, and may therefore be useful for achieving remarkable increases in gluteus maximus strength and hypertrophy. Furthermore, the horizontal nature of the hip thrust may mean that it carries over well to horizontally-oriented activities, such as pushing or sprinting. In order to test these hypotheses, a number of studies were carried out. Interestingly, it was found that there is no statistically significant difference in electromyographic amplitude between squat parallel, full, and front squat variations, and that there is no difference ($p > 0.05$) in electromyographic amplitude between barbell, American, and band hip thrust variations. The barbell hip thrust elicits much greater (mean upper gluteus maximus ES = 1.55; mean lower gluteus maximus ES = 1.65; mean biceps femoris ES = 1.58) hip extensor electromyographic activity than does the parallel squat, and is also beneficial for concentric force outputs (ES = 0.48). The squat, however, displayed a number of kinetic and temporospatial advantages over the hip thrust, including greater bar displacement (ES = 5.59) and potentially total work, impulse, and repetition time (ES = 0.51–1.00). A randomized-controlled trial was then performed to investigate how these differences transfer to training in adolescent male athletes. It appears that the hip thrust effectively improves a number of performance measures, including 20 m sprint times (ES = 1.14) and isometric mid-thigh pull strength (ES = 1.11). The front squat

effectively increased vertical jump ($ES = 1.11$). Between-group comparisons revealed a number of benefits to the hip thrust over the front squat, including 10 and 20 m sprint times ($ES = 0.32$ and 0.39 , respectively) and isometric mid-thigh pull strength ($ES = 1.35$ and 0.76 for absolute and normalized, respectively), and possible trivial benefits for horizontal jump performance ($ES = 0.15$). The front squat displayed a possibly beneficial effect for vertical jump performance ($ES = -0.47$). Finally, a single-subject six-week training study was conducted on monozygotic twins, wherein gluteus maximus hypertrophy and strength outcomes were measured. The squat and hip thrust exercises both increased upper and lower gluteus maximus thickness (upper: 20.7% (squat) vs. 23.5% (hip thrust); lower: 20.3% (squat) vs. 23.1% (hip thrust)), with the hip thrust being more effective at increasing upper gluteus maximus thickness compared to the squat (upper: 2.73%; lower: 2.89%). The hip thrust increased maximum horizontal force, 1 RM hip thrust, and 1 RM squat strength (31.8–65.0%), whereas the squat only increased 1 RM squat and 1 RM hip thrust (19.9–63.2%). This thesis provides evidence that the direction of the force vector in relation to the exerciser's body plays a role in determining the transfer to performance.

PREFACE

1.1 Rationale and Significance of Research

The role and importance of hip extension moment production in sport is well studied, especially as it pertains to sprinting and jumping performance (Belli, Kyrolainen, & Komi, 2002; Blazevich, 2000; Guskiewicz, Lephart, & Burkholder, 1993; Pandy & Zajac, 1991; Schache et al., 2011). While there are a multitude of methods to strengthen the hip extensor musculature – namely, the gluteus maximus and hamstrings – there is a paucity of research pertaining to the implications of the force vector's direction during resistance training (Los Arcos et al., 2014; Ramirez-Campillo et al., 2014; Randell, 2011; Singh & Singh, 2013; Thomasian, 2015). A force vector can be applied in an infinite number of directions, but there are two primary directions in which the hip extensors can be loaded: vertically and horizontally. The former involves movements such as the back squat, wherein an axial load is placed on the body, and upon descent and hip flexion, the external moment arm of the hips to the system center of gravity increases, thus requiring the production of a hip extension moment. Conversely, the latter involves the application of a force that is perpendicular to the length of the body, such as in the barbell hip thrust. Randell, Cronin, Keogh, and Gill (2010) discussed the possible implications of exercise force vectors – more specifically, the transference to performance of both horizontal and vertical force vector training modalities. However, the kinetics and kinematics, in addition to the transference to acceleration and power of these exercises, have not yet been elucidated.

The gluteus maximus is a strong hip extensor and produces the greatest electromyographic (EMG) amplitude at end-range hip extension (Fischer & Houtz, 1968; Worrell et al., 2001). Fischer and Houtz (1968) noted that the hamstrings predominantly perform exercises that extend the hip from flexion, while extension beyond standing position is associated with the gluteus maximus. This means that resistance training exercises that utilize vertical force vectors, such as the back squat, do

not load the gluteus maximus when it is most active, potentially meaning that they are a suboptimal training stimulus for hypertrophy and strengthening the gluteus maximus. The hamstrings are also strong hip extensors and knee flexors and play an important role in sprinting (Thelen et al., 2004). The squat, an exercise of interest with a vertical force vector, has been shown to have a descending hip extension moment curve from hip flexion to extension (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001), which is opposite to that of sprinting, which involves increasing hip extension torque throughout the hip extension range of motion and a maximum hip extension torque value just after foot strike (Bezodis, Kerwin, & Salo, 2008; Mann, 1981). The back squat has also been shown to be an ineffective exercise for hamstring development (Ebben, Leigh, & Jensen, 2000).

Conversely, it is possible that the barbell hip thrust, an exercise with a horizontal force vector, would have a more constant hip extension moment throughout the hip range of motion, more similar to that of sprinting compared to the back squat. If this is true, it is plausible that the barbell hip thrust may transfer better to sprint running than do traditional standing exercise due to the increased “hip extension moment specificity” to sprint running compared to that of traditional standing strength exercises. Furthermore, sprint performance has been correlated with horizontal, but not vertical, force production (Brughelli, Cronin, & Chaouachi, 2011a; Hunter, Marshall, & McNair, 2005; Morin et al., 2012; Morin, Edouard, & Samozino, 2011), and because adaptations are range of motion-specific (Barak, Ayalon, & Dvir, 2004), it is hypothesized that exercises with horizontal force vectors, such as the barbell hip thrust, may be more effective at increasing sprinting speed and acceleration. To date, the only study to include the barbell hip thrust did not show an increase in sprinting speed (Mendiguchia et al., 2014), but more research is needed. The back squat may, however, transfer better to vertical jump performance, as both utilize vertical force vectors, and because it has

been shown that squat strength and vertical jump height increase proportionally (Wilson, Murphy, & Walshe, 1996).

Electromyography (EMG) is a method by which muscle activation can be measured and quantified, and it is presumed that a muscle's EMG amplitude is related to that muscle's force output (De Luca, 1997). Thus, it is useful for acute or mechanistic sports science research. In order to account for inter-individual differences, increase reliability, and allow for inter-study comparisons, normalization procedures are often employed (Halaki & Ginn, 2012). One method by which EMG can be normalized is via a maximum voluntary isometric contraction (MVIC), wherein subjects maximally contract the muscle of interest in a specific isometric condition, and the amplitude obtained during that contraction serves as a denominator for future amplitudes in order to obtain a percentage of MVIC. In numerous studies, however, many different positions have been used for gluteus maximus MVIC testing. For example, Vakos, Nitz, Threlkeld, Shapiro, and Horn (1994) used a combination of a prone and side lying postures and had subjects resist hip flexion and adduction. McGill, McDermott, and Fenwick (2009) had subjects resist maximum extension in a Beiring-Sorensen (isometric back extension) position. Robertson, Wilson, and St Pierre (2008) used a maximum contraction during a partial squat with heels elevated. Queiroz, Cagliari, Amorim, and Sacco (2010) used the recommendations of a European project with the goal of standardizing surface EMG named Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM), which involved placing subjects in a prone position and having them extend the entire thigh against resistance with straight legs. Many studies utilized the recommendations of Kendall, which involves a manual muscle test in a prone position with bent legs (Lewis & Sahrmann, 2009; Oliver & Dougherty, 2009). Unfortunately, a surprising number of studies such as Escamilla, Francisco, Kayes, Speer, and Moorman (2002) failed to report the MVIC position, and

some omitted the standardization process altogether (Caterisano et al., 2002; McCaw & Melrose, 1999). The determination of a gold standard MVIC position is essential for research reliability in order to make it possible to compare EMG amplitudes between studies.

1.2 Purpose of Research

The purpose of the thesis was to answer the overarching question: Does force vector direction play a predominant role in transference? To achieve these ends, it was first necessary to review the current literature pertaining to gluteus maximus EMG amplitudes in a number of resisted hip extension exercises. Thereafter, hip extension moment-angle curves of different exercises were explored and a novel exercise – the barbell hip thrust, which utilizes a horizontal force vector – was developed and described. This exercise was then compared to the squat, which utilizes a vertical force vector, in a number of acute and longitudinal variables, including EMG amplitudes of the hip and thigh musculature, kinetics, gluteus maximus hypertrophy, and changes in performance.

The aforementioned objectives will allow for the systematic discovery, or lack thereof, of the implications of vertical or horizontal force vectors on sprinting and vertical jump performance – more specifically, the transference of training of the front squat versus barbell hip thrust.

1.3 Significance of Thesis

Though it is well known that strength training can improve acceleration, speed, and power, there is a paucity of research examining the effects of common hip strengthening exercises on performance. While the squat exercise and Olympic lift

variations have been heavily researched, exercises such as the hip thrust have not been researched in any detail.

Pilot research by the author of this thesis indicated that gluteus maximus activation was maximized during the hip thrust exercise. A cursory biomechanical analysis suggested that the hip thrust exercise produced significantly greater end-range hip extension torque in comparison to the squat exercise. Though a strong case could be made for incorporating the hip thrust exercise into athletic programming, research needs to be conducted in order to validate or refute hypotheses regarding the hip thrust's level of gluteal muscle activation, level of instantaneous torque production at end-range hip extension, and transference to sport.

The literature contains a vast amount of electromyographic (EMG) research pertaining to gluteus maximus activation, but two key problems exist. First, it is difficult to make comparisons between studies due to the myriad of maximum voluntary isometric contraction (MVIC) positions used by researchers during their studies. Second, a comprehensive examination of different hip strengthening exercises measuring gluteus maximus activation has yet to be conducted. Typically, gluteal EMG studies involve bodyweight physical therapy exercises or just a handful of challenging exercises. To the knowledge of this author, no study exists that comprehensively measures gluteal muscle activation during a variety of hip strengthening exercises using different force vectors under heavy loading. This research could provide useful information for strength coaches, personal trainers, and physical therapists.

Finally, though we know that horizontal force production is valuable in many different sports including those involving sprinting, no training study has determined specific methods or exercises that can be used to increase horizontal force or whether increasing horizontal force leads to increases in velocity. We do know that the hip joint is of utmost importance for speed and power production and is very likely the limiting

joint in terms of maximum speed and acceleration. Hip extension torque varies considerably throughout the hip extension range of motion during a sprint cycle and throughout various strength exercises. Exercises that maximize torque at end-range hip extension (i.e., horizontal hip extension exercises) may be better suited for developing maximum speed in comparison to exercises that maximize torque at initial-range hip extension (i.e., vertical hip extension exercises), but no such studies exist comparing the effects of the two categories on performance. A study examining this area of research is imminent.

Understanding how vertical and horizontal force vectors affect training outcomes will help strength and conditioning coaches improve specificity, thereby optimizing transference and performance. Should the hypotheses that barbell hip thrusts are better for improving sprinting outcomes and that front squats are better for improving vertical jump hold true, then coaches and athletes may benefit by prioritizing the programming of each exercise for their respective beneficial outcomes. For example, should the barbell hip thrust be better for improving sprinting acceleration, then perhaps it would be beneficial to prioritize the barbell hip thrust over the front squat.

1.4 Structure of Thesis

This thesis is comprised of four main inter-linking sections that answer the overarching question: Does force vector direction play a predominant role in transference? The first section (Chapter 2) is comprised of one literature review, examining the gluteus maximus EMG activity elicited by different exercises. The second section (Chapter 3) has two parts. The first describes the barbell hip thrust, a new exercise that incorporates horizontal loading. The second part describes the kinetic differences between different hip extension exercises. The third section (Chapters 4–7) is comprised of acute

research, examining the EMG activity elicited by different types of squats and hip thrusts and kinetic differences between the squat and hip thrust. The third section will also incorporate reliability data for the maximum horizontal push test. The fourth and final section will be comprised of two training studies (Chapters 10 and 11). The first will examine the effects of the front squat and hip thrust on performance in teenage athletes. The second will be a single subject design, examining the effects of squatting versus hip thrusting on gluteus maximus hypertrophy on identical twins.

The studies are presented in the format of the journal for which they were written, with the exception that each study is preceded by an explanatory prelude rather than an abstract. There are minor formatting changes to some chapters to improve consistency – new images were used in Chapter 3.1, for example. The final chapter consists of general conclusions and recommendations for athletes and strength and conditioning practitioners. An overall reference list from the entire thesis has been collated at the end of the final chapter in APA (6th ed.) format. The appendices present all the relevant material from the studies including the abstracts from the scientific studies, ethics approval, participant information sheets, questionnaires, informed consent forms, and additional data. The literature review was written to summarise the research pertinent to each of the experimental papers presented in this thesis. The review clearly demonstrates the deficiencies and limitations in this area in terms of strength and conditioning practice and establishes the significance of the scientific studies presented in the ensuing chapters. Please note that there is some repetition throughout the thesis, owing to the format in which the overall thesis is presented– that is, thesis by publication.

***A REVIEW OF GLUTEUS MAXIMUS EMG ACTIVITY DURING
RESISTED HIP EXTENSION EXERCISE***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**Strength and Conditioning Journal
In Review (Appendix 3a)**

2.0 Lead Summary

Hip extension exercises are essential in strength and conditioning. The primary hip extensors are the gluteus maximus, hamstrings, and adductors, and the contribution of each varies throughout the hip flexion-extension arc of motion. There is a scarcity of well-conducted resistance training studies examining gluteus maximus electromyography (EMG) activity, and to date, no comprehensive study exists that compares the gluteus maximus EMG activity to that of a variety of common resisted hip extension exercises. This article reviews the current research pertaining to gluteus maximus EMG activity during resisted hip extension exercise and provides direction for future research.

2.1 Introduction

In strength and conditioning programs, resisted hip extension exercises are thought to reduce the risk of hamstring strains (Brughelli & Cronin, 2008; Turner et al., 2014), increase acceleration, speed, and power (Behrens & Simonson, 2011; Dawes & Lentz, 2012; May, Cipriani, & Lorenz, 2010; Waller, Gersick, Townsend, & Ford, 2014), and prevent the likelihood of developing excessive anterior pelvic tilt (Waryasz, 2010). Common resisted hip extension exercises prescribed by strength and conditioning coaches include reverse lunges (Graham, 2011), front squats (Bird & Casey, 2012), deadlifts (Bird & Barrington-Higgs, 2010), back extensions (Contreras, Cronin, Schoenfeld, Nates, & Sonmez, 2013), barbell hip thrusts (Contreras, Cronin, & Schoenfeld, 2011), leg presses (Graham, 2004), and power cleans (Graham, 2000).

The gluteus maximus, a hip extensor often trained through hip extension exercises, elicits high levels of activation and muscle force output during sprint running (Bartlett, Sumner, Ellis, & Kram, 2014; Dorn, Schache, & Pandy, 2012; Kyrolainen,

Avela, & Komi, 2005) and is responsible for producing hip extension, hip external rotation, hip abduction, and posterior pelvic tilt (Neumann, 2010). On account of this versatility, researchers have recently likened the gluteus maximus to a multifunction Swiss army knife (Bartlett et al., 2014). However, the hip extension function of the gluteus maximus is of primary importance for several reasons: first, hip extension plays a dominant role in sagittal plane activities, such as sprinting and jumping (Beardsley & Contreras, 2014); second, and perhaps less well known, hip extension actually plays a dominant role in frontal and transverse plane activities, such as cutting from side to side and striking (Inaba, Yoshioka, Iida, Hay, & Fukashiro, 2013; Lenetsky, Harris, & Brughelli, 2013; Shimokochi, Ide, Kokubu, & Nakaoji, 2013); third, since hip extension and posterior pelvic tilt are one and the same, the gluteus maximus is a primary sagittal plane stabilizer of the pelvis (Neumann, 2010; Noe, Mostardi, Jackson, Porterfield, & Askew, 1992); fourth, relying on the gluteus maximus rather than the hamstrings for hip extension may better protect the knees during both lunges (Alkjaer, Wieland, Andersen, Simonsen, & Rasmussen, 2012) and squats (Bryanton, Carey, Kennedy, & Chiu, 2015); fifth, there is evidence showing that focusing attention on the gluteus maximus during hip extension leads to higher gluteus maximus and lower hamstrings involvement, indicating that it is possible to augment the synergist muscle force contribution to the hip extension net joint moment (Lewis & Sahrman, 2009); sixth, there is evidence suggesting that better strongman competitors more effectively utilize their gluteus maximus than do their weaker counterparts during heavy hip extension training (McGill et al., 2009); and seventh, there is evidence suggesting that triathletes suffering from hamstring cramps can strengthen the gluteus maximus, and in turn, use them more when running, indicating that it is possible to alter the muscle force contribution to hip extension net joint moment during endurance activity (Wagner et al., 2010). Therefore, it is of great interest for researchers and coaches alike to determine the best resistance

exercises for strengthening the gluteus maximus and improving hip extension performance.

Previous research investigating the behavior of gluteus maximus EMG activity during isometric and dynamic tasks has yielded interesting data. Yamashita (1988) found that single joint isometric hip extension exercise led to significantly greater gluteus maximus activation compared to multiple joint isometric hip and knee extension exercise, even when controlling for hip extension moment requisites. Given that recent research has shown that activation and hypertrophic adaptations are linked to one another (Wakahara, Fukutani, Kawakami, & Yanai, 2013; Wakahara et al., 2012), one could surmise, based on this data, that single joint exercises for the gluteus maximus are equally or more effective than multiple joint exercises for the purposes of increasing gluteus maximus development, at least when considering isometric muscle actions. However, it is currently difficult to assess why this might be the case.

Furthermore, bending the knee and thereby shortening the hamstrings leads to increased gluteus maximus EMG activity during prone hip extension, as reported by Sakamoto, Teixeira-Salmela, de Paula-Goulart, de Moraes Faria, and Guimaraes (2009), Kwon and Lee (2013), and Park and Yoo (2014). This implies that the kinematics of a resisted hip extension movement may have a direct impact on the recruitment of the gluteus maximus and possibly the resulting training effect as well. When the knee is bent during prone hip extension and back extensions, it may be that the gluteus maximus is more active because the hamstrings are in active insufficiency and therefore their capacity to produce force is reduced.

It appears that the gluteus maximus activates to a much greater degree at short muscle lengths compared to long muscle lengths. The gluteus maximus is shortened via hip extension/hyperextension, hip abduction, hip external rotation, and posterior pelvic tilt, and each of these actions have been shown to increase gluteus maximus activity.

Worrell et al. (2001) found that the gluteus maximus elicited significantly greater EMG activity (94.0% vs. 64.0% MVIC-EMG) at end-range hip extension compared to hip extension in the flexed position, as noted almost 50 years ago by Fischer and Houtz (1968). Kang, Jeon, Kwon, Cynn, and Choi (2013) and Suehiro et al. (2014) found that gluteus maximus EMG activity is significantly greater (29.6 vs. 20.2% and 22.5 vs. 14.1%, respectively) when the hips are abducted compared to when the hips are in neutral position. Sakamoto et al. (2009) and Suehiro et al. (2014) found that gluteus maximus EMG activity is significantly greater (22.5% vs. 12.7% and 41.0% vs. 22.5%, respectively) when the hips are externally rotated compared to when the hips are in neutral position. Finally, Queiroz et al. (2010), Tateuchi, Taniguchi, Mori, and Ichihashi (2012), and Tateuchi et al. (2013) found that gluteus maximus EMG activity is significantly greater ($r = 0.52$) when the pelvis is posteriorly tilted compared to when the pelvis is anteriorly tilted or in neutral position. Further support for posterior pelvic tilt leading to increased gluteus maximus activity can be observed in studies examining abdominal draw-in maneuvers (ADIM) during hip extension tasks, as the ADIM reduces anterior pelvic tilt and leads to greater gluteus maximus activity (Kim & Kim, 2015; Oh, Cynn, Won, Kwon, & Yi, 2007).

It is important to investigate whether these studies are in line with research examining resisted hip extension during common strength training exercises. The purpose of this article will be threefold: first, to review the research pertaining to gluteus maximus EMG activity during dynamic resisted hip extension exercise; second, to discuss the application of these findings to exercise program design; and third, to provide direction for future research.

2.2 Search Strategy

A literature search was conducted via PubMed, Google Scholar, and SPORTDiscus databases. Combinations of the following terms were searched: gluteus maximus, gluteal, glute, squat, back, front, box, goblet, Zercher, counterbalance, deadlift, conventional, sumo, hex bar, Romanian, RDL, stiff legged, straight leg, lunge, forward, reverse, leg press, hip sled, back extension, Roman chair, swing, split, pull, rack, step up, single leg, single limb, one leg, one legged, Bulgarian, good morning, bridge, hip thrust, kickback, donkey kick, hyperextension, pull through, clean, snatch, jump, hip extension, hip extensor, posterior chain, barbell, dumbbell, cable, band, kettlebell, sled, vest, exercise, strongman, Olympic weightlifting, powerlifting, electromyography, electromyographic, EMG, muscle muscular, activity, and activation.

Articles were omitted if the studies did not utilize external resistance (external resistance could involve barbell, dumbbell, kettlebell, elastic band, chain, sled, vest, strongman implement, specialty barbell, ankle weight, cable, machine, and more), if they did not examine dynamic exercises, if they did not examine hip extension exercises, if they did not normalize data to a specific gluteus maximus MVIC position, and if they did not examine healthy male or female subjects. In other words, studies that investigated only bodyweight exercises, isometric exercises, or hip abduction, hip external rotation, or posterior pelvic tilt gluteus maximus exercises were excluded, along with studies that failed to normalize their data or normalized data to submaximal reference movements and those that investigated injured subjects or subjects in pain. Once the articles were filtered accordingly, studies were cross-referenced in order to ensure comprehensiveness. Exactly 154 studies examining gluteus maximus EMG during gluteus maximus exercises were found. However, only 18 of these studies met the aforementioned criteria as of July 15, 2015.

2.3 Squat Studies

Six studies to date have examined gluteus maximus activity during resisted squats while normalizing the data to MVIC (Andersen et al., 2006; Aspe & Swinton, 2014; Gomes et al., 2015; Lynn & Noffal, 2012; Manabe, Shimada, & Ogata, 2007; Yavuz, Erdag, Amca, & Aritan, 2015) (Table 2.1). Gluteus maximus EMG activity during different squat variations (back, front, dumbbell racked, and dumbbell counterbalanced) was examined at loads ranging from 30-100% of 1RM for barbell squat variations and 3.4–4.5 kg with dumbbell squat variations. The main findings were that: one, gluteus maximus EMG activity was markedly higher during lifting phases compared to lowering phases of the movement; two, front and back squats elicited nearly identical levels of gluteus maximus EMG activity when identical relative loads were used; two, faster bar speeds elicited greater gluteus maximus EMG activity compared to slower bar speeds; four, knee wraps were associated with increased gluteus maximus EMG activity; five, positioning dumbbells in the counterbalanced position involved greater gluteus maximus EMG activity than positioning dumbbells in the racked position during squats; and six, gluteus maximus EMG activity increased with increasing load.

Table 2.1 Resisted squat exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
Manabe et al. (2007)	Back squat 30% of 1RM Slow speed Normal speed Quick speed	Not specified	Prone hip extension	Mean Eccentric activity: ~ 8, 10, and 25% for slow, normal, and quick speeds, respectively. Concentric activity: ~17, 56, and 55% for slow, normal, and quick speeds,

				respectively.
Aspe and Swinton (2014)	Back squat Overhead squat 60% of 3RM 75% of 3RM 90% of 3RM	Half the distance between the trochanter and sacral vertebrae in the middle of the muscle	Using a glute-hamstring apparatus with the subject in a prone position with the knee flexed to 135 degrees as manual resistance was applied by the researcher across the posterior shoulder	Mean iEMG Back squat eccentric phase at 60, 75, and 90% of 3RM was 19.2, 24, and 24% of MVIC Back squat concentric phase at 60, 75, and 90% of 3RM was 66.9, 85.7, and 92.7% of MVIC Overhead squat eccentric phase at 60, 75, and 90% of 3RM was 14.4, 13.4, and 18.6% of MVIC Overhead squat concentric phase at 60, 75, and 90% of 3RM was 49.0, 66.9, and 60.9% of MVIC
Yavuz et al. (2015)	Front squat Back squat 1RM	50% on the line between the sacral vertebrae and the greater trochanter, corresponding with the greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter	Hip extension with both extended and flexed knee positions with slightly outward rotated legs at $\sim 20^\circ$ of hip hyperextension	Mean Front squat: 37.2% (30.0% during eccentric phase and 46.6% during concentric phase) Back squat: 37.1% (28.8% during eccentric phase and 47.3% during concentric phase)
Gomes et al.	Back squat	50% of the	Prone position	iEMG

(2015)	With knee wraps Without knee wraps 60 of 1RM loads 90% 1RM loads	distance between the sacral vertebrae and the greater trochanter	with knee flexed at 90° with resistance placed on the distal region of thigh with pelvis in stabilized position	~ 45% at 60% of 1RM without wraps ~ 60% at 60% of 1RM with wraps ~ 80% at 90% of 1RM without wraps ~ 90% at 90% of 1RM with wraps
Lynn and Noffal (2012)	Racked dumbbell squat Counterbalance dumbbell squat 7.5 – 10 lb dumbbells	In line with muscle fibers, avoiding motor point	Prone bent-leg hip extension	Peak Racked: 20.0% Counterbalance: 23.1% iEMG Concentric activity: 99.4% for racked and 124.0% for counterbalance Eccentric activity: 60.2% for racked and 64.7% for counterbalance
Andersen et al. (2006)	Back squat 5 reps of 10RM	Middle of muscle	Average of 10 and 90° maximum isometric hip extension	Mean 55%

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.4 Deadlift Studies

Two studies to date have examined gluteus maximus EMG activity during resisted deadlifts while normalizing the data to MVIC (Escamilla et al., 2002; Noe et al., 1992) (Table 2.2). Gluteus maximus EMG activity during different deadlift variations (conventional, sumo, and isokinetic) was examined at 12 RM loads and isokinetic

speeds of 30.5 and 45.7 cm/sec. The main findings were that: one, conventional and sumo deadlifts lead to nearly identical levels of gluteus maximus EMG activity; two, weightlifting belts do not significantly alter gluteus maximus EMG activity; and three, both untrained and advanced subjects activate their glutei maximi to similar extents during isokinetic deadlifts.

Table 2.2 Resisted deadlift exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
Escamilla et al. (2002)	Conventional deadlifts Sumo deadlifts With a belt Without a belt 12RM Loads	Not specified	Prone bent-leg hip extension	Mean Conventional deadlift: 35.0% Sumo deadlift: 37.0% With belt: 35.0% No belt: 37.0%
Noe et al. (1992)	Maximum isokinetic deadlifts 30.5 cm/sec 45.7 cm/sec	Midway between the posterosuperior iliac spine and the ischeal tuberosity	Maximum contraction in the form of a buttock pinch in a partially forward bent position	iEMG ~ 35-70% throughout ROM for weightlifters at 30.5 cm/sec ~ 35-72% throughout ROM for weightlifters at 45.7 cm/sec ~ 30-70% throughout ROM for normal subjects at 30.5 cm/sec ~ 34-78% throughout ROM for normal subjects at 45.7 cm/sec

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.5 Single Limb Squat Studies

Three studies to date have examined gluteus maximus EMG activity during resisted single limb squatting movements, while normalizing the data to MVIC (Jakobsen, Sundstrup, Andersen, Aagaard, & Andersen, 2013; Simenz, Garceau, Lutsch, Suchomel, & Ebben, 2012; Sundstrup et al., 2014) (Table 2.3). Gluteus maximus EMG activity during a variety of types of single limb squats (step up and lunge variations) were examined at loads ranging from 6 to 10 RM and from 33-100% of 1 RM. The main findings were: one, gluteus maximus EMG activity during the lifting phase far exceeded gluteus maximus EMG activity during the lowering phase in step ups; two, gluteus maximus EMG activity during elastic band resisted lunges was comparable to gluteus maximus EMG activity during dumbbell lunges at identical relative loads; three, heavier loading during lunges elicited greater levels of gluteus maximus EMG activity; and four, gluteus maximus EMG activity during ballistic lunges with medium loads was comparable to gluteus maximus EMG activity during standard lunges with heavy loads.

Table 2.3 Resisted single limb squat exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
Simenz et al. (2012)	Step-up from 18" box 6RM dumbbell load	One-third of the distance from the second sacral spine to the greater trochanter	Prone at approximately 70 hip flexion on a decline bench	Mean Eccentric activity: 97.5% Concentric activity: 241%
Sundstrup et al. (2014)	Band resisted lunge Dumbbell lunge 10RM loads	50% on the line between the sacral vertebrae and the greater trochanter. This position corresponds with the	Hip extension (type not specified)	Peak Band lunges: ~ 42.0% during eccentric phase and ~63.0% during concentric

		greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter		phase Dumbbell lunges: ~38.0% during eccentric phase and ~48% during concentric phase
Jakobsen et al. (2013)	Band resisted lunge Dumbbell lunge Ballistic (medium load), Heavy (100% of 10RM) Medium (66% of 10RM) Light (33% of 10RM)	Not specified	Prone bent-leg hip extension	Mean Ballistic: ~ 34.0-61.0% throughout ROM Heavy: ~ 42.0-58.0% throughout ROM Medium: ~ 30.0-43.0% throughout ROM Light: ~ 22.0-32.0% throughout ROM

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.6 Other Resisted Hip Extension Studies

Five studies to date have examined gluteus maximus EMG activity during other resisted hip extension exercise while normalizing the data to MVIC (De Ridder, Van Oosterwijck, Vleeming, Vanderstraeten, & Danneels, 2013; Frost, Beach, Fenwick, Callaghan, & McGill, 2012; MacAskill, Durant, & Wallace, 2014; Queiroz et al., 2010; Youdas et al., 2014) (Table 2.4). Gluteus maximus EMG activity during a variety of other types of resisted hip extension exercises (prone bent-leg hip extension, sled towing, spring-loaded resisted hip extension, standing band resisted hip extension, partial back extensions, and partial reverse hyperextensions) was examined at a variety

of loads including 10 RM, 20-80% bodyweight loads, 8 to 9 kg, and 60% of 1 RM. The main findings were: one, resisted prone bent-leg hip extension resulted in exceptionally high levels of gluteus maximus EMG activity; two, bent and straight legged sled towing led to similar levels of gluteus maximus EMG activity; three, gluteus maximus EMG activity was significantly higher when the pelvis was in posterior tilt compared to when in neutral or anterior tilt; four, the moving limb elicited more than three times the gluteus maximus EMG activity versus the stance limb during band walks; and five, the back extension exercise elicited greater gluteus maximus EMG activity than the reverse hyper exercise at identical relative loads.

Table 2.4. Resisted hip extension exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
MacAskill et al. (2014)	Weighted prone bent-leg hip extension 10RM (ankle weight on distal thigh)	33% of the distance between the second sacral vertebra and the greater trochanter	Prone bent-leg hip extension	Mean 100%
Frost et al. (2012)	Forward sled towing Bent legs Straight legs 20% bodyweight load 50% bodyweight load 80% bodyweight load	At the middle of the muscle belly approximately 4 cm lateral to the gluteal fold	Resisted maximum extension in the Biering Sorensen position	Peak Bent leg: 48.1-65.2% Straight leg: 49.7-63.2%
Queiroz et al. (2010)	Spring-loaded resisted hip extension in quadruped position	On the midline between the sacral vertebrae and the greater trochanter, over the greatest	Prone hip extension	Mean Neutral inclined torso: 17.6% concentric

	Neutral inclined torso Neutral parallel torso Anterior pelvic tilt Posterior pelvic tilt	prominence of the middle of the buttocks		activity, 10.7% eccentric activity Neutral parallel torso: 13.6% concentric activity, 7.93% eccentric activity Anterior pelvic tilt: 17.8% concentric activity, 11.1% eccentric activity Posterior pelvic tilt: 40.9% concentric activity, 28.3% eccentric activity
Youdas et al. (2014)	Standing band hip extension Around 8-9 kg of band tension	Half the distance between the greater trochanter of the femur and the spinous process of the second sacral vertebra along an oblique angle at the level of the greater trochanter or slightly above	Prone bent-leg hip extension	Mean 39.6% for moving limb 12.5% for stance limb
De Ridder et al. (2013)	Partial weighted back extension Partial weighted reverse hyper 60% of 1RM	Midway between the posterosuperior iliac spine and the ischial tuberosity	Prone bent-leg hip extension	Mean Back extension: – 44.9% concentric activity and ~33.1% eccentric activity Reverse hyper:

				– 30.3% concentric activity and ~20.3% eccentric activity
--	--	--	--	---

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.7 Leg Press Studies

Three studies to date have examined gluteus maximus EMG activity during machine leg presses while normalizing the data to MVIC (Andersen et al., 2006; Augustsson et al., 2003; Sundstrup et al., 2014) (Table 2.5). Gluteus maximus EMG activity during a variety of types of leg presses (machine, one leg, and hip sled) were examined at 10 RM loads. The main finding was that the lowering phase of leg press movement elicited significantly lower gluteus maximus EMG activity than the lifting phase of leg press movements.

Table 2.5. Resisted leg press exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
Augustsson et al. (2003)	Machine leg press 10 RM	Electrode placement was determined by placing subjects in the appropriate test positions and identifying the muscle bellies of interest via isometric contraction	Prone hip extension knee flexion	Mean ~ 65.0%
Sundstrup et al. (2014)	One legged leg press 10 RM loads	50% on the line between the sacral vertebrae and the greater trochanter. This position corresponds with the	Hip extension (type not specified)	Peak Eccentric phase: – 31.0% Concentric phase: ~ 51.0%

		greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter		
Andersen et al. (2006)	Leg press 5 reps of 10 RM	Middle of muscle	Average of 10 and 90 degree maximum isometric hip extension	Mean 60.0%

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.8 Kettlebell Studies

One study to date has examined gluteus maximus activity during kettlebell training while normalizing the data to MVIC (McGill & Marshall, 2012) (Table 2.6). Gluteus maximus EMG activity during a variety of types of kettlebell exercises (swing, swing with kime, and swing to snatch) were examined at 16 kg loads. The main findings were: one, adding a kime (a brief muscular pulsing of the abdominals at the top of the swing) slightly increased gluteus maximus EMG activity; and two, kettlebell swings elicited markedly greater gluteus maximus EMG activity than kettlebell swings to snatches. A case study examining a highly trained subject (Pavel Tsatsouline) revealed that 32 kg kettlebell swings elicited approximately 100% peak gluteus maximus EMG activity, suggesting that greater loads in the swing lead to higher levels of gluteus maximus activation.

Table 2.6. Resisted kettlebell exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
McGill and Marshall (2012)	Kettlebell swing Kettlebell swing w/kime Kettlebell swing to snatch 16 kgs	In the middle of the muscle belly approximately 6 cm lateral to the gluteal fold	Biering-Sorensen AND prone bent-leg hip extension against manual resistance (whichever was greatest)	Peak Swing: 76.1% Swing w/chime: 82.8% Swing to snatch: 58.1%

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.9 Strongman Studies

One study to date has examined gluteus maximus EMG activity during strongman training while normalizing the data to MVIC (McGill et al., 2009) (Table 2.7). Gluteus maximus EMG activity during a variety of types of strongman exercises (farmer's walk, suitcase carry, yoke walk, log lift, tire flip, Atlas stone lift, and keg walk) was examined at varying loads. The main findings were: one, Atlas stone lifts and tire flips led to exceptionally high levels of gluteus maximus EMG activity; and two, the suitcase carry and keg walk lead to markedly less gluteus maximus EMG activity than the other strongman exercises examined in the study.

Table 2.7. Resisted strongman exercise studies that have examined gluteus maximus activity and normalized the data to a gluteus maximus MVIC position.

Study	Exercises & Loads	Gluteus Maximus Electrode Site Placement	Gluteus Maximus MVIC Position	Gluteus Maximus EMG Data
McGill et al. (2009)	Farmer's walk Suitcase carry Yoke walk Log lift Tire flip Atlas stone lift Keg walk Loads Varied	Middle of muscle belly approximately 4 cm lateral to the gluteal fold	Resisted maximum extension in the Biering Sorensen position	Peak Farmer's walk: 114% Suitcase carry: 50.5% (right hand) and 78.2% (left hand) Yoke walk: 113% Log lift: 158% Tire flip: 200% Keg walk: 64.5% (left side) and 89.7% (right side) Atlas stone lift: 259%

1RM = one repetition maximum, RM = repetition maximum, MVIC = maximum voluntary isometric contraction, EMG = electromyography, iEMG = integrated electromyography, ROM = range of motion

2.10 Limitations

One must be cognizant of a number of limitations when interpreting EMG research, as comparing EMG studies is complicated and can be problematic. At the very least, in order to compare the EMG activity between two studies with high levels of accuracy, their electrode site placements, MVIC positions, data processing, and amplitude presentations should be identical, and variables such as range of motion, relative load, effort, tempo, fatigue, gender, age, and training status should be similar (De Luca, 1997; Raez, Hussain, & Mohd-Yasin, 2006). This is rarely the case in EMG research, as different groups of researchers utilize different techniques and have differing preferences with regards to how they measure and present their data.

To exemplify the aforementioned points, it is useful to discuss two studies examining gluteus maximus EMG activity. Worrell et al. (2001) reported on gluteus maximus EMG activity during maximum voluntary isometric hip extension torque production at different hip flexion angles. They reported that gluteus maximus EMG activity was 64.3% of MVIC at 90° hip flexion, 80.1% of MVIC at 60° hip flexion, 84.4% of MVIC at 30° hip flexion, and 93.8% of MVIC at 0° hip flexion. Therefore, when Simenz et al. (2012) used an MVIC position at 70° hip flexion, this position almost certainly yielded far lower values of gluteus maximus EMG activity than would have been observed if an MVIC position at 0° hip flexion had been used. When normalizing the loaded step up to this inferior MVIC position, the authors understandably reported unusually high gluteus maximus EMG activity. This was most likely caused by the much smaller gluteus maximus EMG activity at MVIC and hence the use of a much smaller denominator. This applies to any study that utilizes an MVIC position for the gluteus maximus with the hips in flexion, including studies by both Noe et al. (1992) and Anderson, Sforzo, and Sigg (2008). Therefore, data from these studies cannot be directly compared to studies that utilized MVIC positions for the gluteus maximus in full hip extension, such as the prone bent-leg hip extension position.

Moreover, examining mean, peak, and integrated EMG (iEMG) data will each yield different results since some exercises seem to possess inherent biomechanical advantages. For example, exercises with high levels of constant tension may elicit high levels of mean or iEMG activity. On the other hand, exercises with high levels of tension at the precise range of motion that maximizes EMG activity – which is often similar to the position used for determining MVICs in EMG research – may elicit high levels of peak activity.

2.11 Practical Applications and Conclusion

Interesting observations can be drawn from the literature reviewed despite some of the aforementioned limitations. First, the Atlas stone lift examined in the McGill et al. (2009) study was found to have the highest level of peak gluteus maximus activity out of all exercises investigated in this review, with 259% MVIC, even when normalized to an MVIC position that involved full hip extension (Biering-Sorensen position). When considering the biomechanics of the Atlas stone lift, it can be seen that the movement involves hip extension through a large range of motion, wherein the strongman rounds his back and posteriorly tilts his pelvis over the stone, then violently extends the hips to lockout in order to raise the stone as high as possible. Tension on the gluteus maximus will therefore be very high throughout the entire range of hip extension motion, which may explain the extremely high level of EMG activity.

In addition, of all exercises included in this review, the weighted prone bent-leg hip extension exercise examined by MacAskill et al. (2014) had the highest level of mean gluteus maximus EMG at 100% MVIC, even when normalized to an MVIC position that involved full hip extension (prone bent-leg hip extension). When considering the biomechanics of the weighted prone bent-leg hip extension exercise, one can conclude that peak tension during the movement will occur at end-range hip extension, and the knees stay bent, which slackens the hamstrings, reducing their contribution and increasing the contribution of the gluteus maximus, thereby explaining the especially high level of mean EMG activity.

The EMG data for these two exercises align with the findings of the aforementioned studies in this review, showing that posterior pelvic tilt increases gluteus maximus EMG activity during hip extension, and that bent-leg hip extension and end-range hip extension yield high levels of gluteus maximus activity during resisted hip extension exercise.

Based on the reviewed literature, it also appears that: rapid hip extension leads to greater gluteus maximus EMG activity compared to slow hip extension; concentric actions yield far greater gluteus maximus EMG activity than eccentric actions; front and back squats and conventional and sumo deadlifts elicit similar levels of gluteus maximus EMG activity; knee wraps and counterbalancing loads increase gluteus maximus activation; weightlifting belts do not affect gluteus maximus activation; kettlebell swings activate the gluteus maximus to a greater degree than do swings to snatches; and elastic resistance bands can be used to effectively activate the gluteus maximus in a comparable manner to free weights.

From the presented data, it is abundantly clear that sports science researchers need to continue investigating gluteus maximus EMG activity during resisted hip extension exercise, as to the authors' knowledge, not a single study exists to date that examines gluteus maximus EMG during barbell hip thrusts, barbell glute bridges, hex bar deadlifts, Zercher squats, Bulgarian split squats, heavy kettlebell swings, heavy sled pushes, barbell clean variations, barbell snatch variations, cable pull throughs, reverse hypers using a pendulum unit, weighted dumbbell back extensions, barbell good mornings, cable kickbacks, and many more.

In addition, researchers should examine gluteus maximus EMG activity during back squats of varying depths, while using identical relative loading to determine whether increasing squat depth elicits increasing levels of gluteus maximus activation. Caterisano et al. (2002) used the same loads for all squat depths when investigating the effects of squat depth on gluteus maximus activity, but the increased gluteus maximus activity they found may likely be due to greater hip extension moment requirements associated with the increasing depth in conjunction with constant loading. Considering that Robertson et al. (2008) found that gluteus maximus EMG activity reaches a

minimum at the bottom of a squat, this topic is especially important to researchers and practitioners alike.

Furthermore, researchers should investigate upper and lower gluteus maximus activity during resisted hip extension exercise. McAndrew, Gorelick, and Brown (2006) found evidence of functional subdivisions existing in the upper, middle, and lower gluteus maximus regions, and Fujisawa et al. (2014) showed that the upper and lower gluteus maximus regions activate uniquely during hip abduction exercise. However, how the upper gluteus maximus region activates compared to the lower gluteus maximus region during various hip extension exercises, such as squats, deadlifts, hip thrusts, and lunges, presently remains a mystery.

To date, not a single comprehensive study has been conducted that compares the gluteus maximus EMG activity between a variety of resisted hip extension exercises under the same conditions (relative loading, MVIC position, electrode site placement, etc.). The American Council on Exercise (ACE) conducted an interesting experiment in 2006 which investigated the gluteus maximus activity between 10 common glute exercises (Anders, 2006). In fact, ACE created a report titled, “Glutes to the Max,” to showcase the results. This experiment is the most comprehensive to date on gluteus maximus EMG activity during resistance training. Unfortunately, the experiment was never published in a peer-reviewed journal, so the data cannot be accepted at face value. Future research should be carried out to investigate gluteus maximus EMG activity between a variety of common gluteus maximus exercises used in strength and conditioning.

Finally, research needs to be conducted to investigate the links between gluteus maximus activity, hypertrophic adaptations, and physical performance. It is still unclear as to whether the exercises that elicit the highest levels of gluteus maximus activity

result in greater gluteus maximus muscular development and performance increases compared to exercises that elicit lower levels of gluteus maximus activity.

3.0 Prelude

The hip thrust and squat exercises will be compared in this thesis in order to determine whether the direction of the force vector of the resistance in relation to the exerciser's body plays a role in the transference to performance. More specifically, this thesis will test whether horizontally-loaded hip extension exercises transfer better to horizontal-oriented strength and power tasks than do vertically-loaded hip extension exercises and vice versa. Though there currently exists a large body of research pertaining to the squat, a complete lack of research exists pertaining to the barbell hip thrust. Since the barbell hip thrust will be performed in Chapters 6, 7, 8, 10, and 11, it is vital that proper exercise technique has been described (Chapter 3.1). In addition, this thesis is predicated on the assumption that the force vector influences the hip extension torque angle curve, which contributes to the nature of transfer to performance. This chapter sought to describe proper technique and training methods associated with the barbell hip thrust and to confirm that vertically-loaded hip extension exercises indeed possess unique hip extension torque angle curves (Chapter 3.2) in comparison to that of horizontally-loaded hip extension exercises. Knowledge of torque angle curves can be taken into consideration alongside MVIC position information inherent to EMG research in order to predict EMG outcomes for different exercises. More specifically, if horizontally loaded hip extension exercises require greater hip extension torque at end-range hip extension in comparison to vertically loaded hip extension exercises, a strong case can be made for their superior transfer to acceleration and sprinting due to end-range hip extension moment requisites.

3.1 BARBELL HIP THRUST TECHNIQUE

Bret Contreras, John Cronin, Brad Schoenfeld

Strength and Conditioning Journal

33(5), 58-61

(Appendix 3b)

3.1.1 Summary

The technique of the barbell hip thrust is described and demonstrated through the use of photographs in this section. An exercise prescription is given.

3.1.2 Type of Exercise

The barbell hip thrust is a biomechanically efficient way to work the gluteal muscles. The exercise can be used to: maximize gluteal muscle activation due to its emphasis on end-range hip extension combined with knee flexion; develop end-range hip extension strength in the gluteus maximus musculature; increase horizontal force production; and increase the contribution of the gluteus maximus relative to the hamstrings during hip extension movement, which may decrease the likelihood of hamstring injuries.

3.1.3 Muscles Used and Benefits

The hip thrust may be used to target the primary hip extensors (gluteus maximus, hamstrings, adductor magnus), secondary hip extensors (adductors, gluteus medius, gluteus minimus), posterior vertebral stabilizers (erector spinae), and knee extensors (rectus femoris, vastis).

This bent-leg, horizontally-loaded hip extension exercise decreases hamstring contribution to hip extension through active insufficiency, which increases the contractile requirements of the glutei maximi musculature. One drawback of typical standing barbell strength exercises is the decreased tension on the hip extensors as the exercise nears lockout and the hips reach a neutral position. Due to the horizontally loaded nature of the hip thrust exercise, tension on the hip musculature is maximized at the exercise's lockout as the hips reach a neutral or a slightly hyperextended position. This corresponds to the zone of hip range of motion involved in ground contact during

maximum speed running. Since vertical forces tend to plateau at approximately 70% of maximum running velocity and horizontal forces continue to rise the higher the velocity, it seems wise to incorporate strategies to work the hips from a horizontal vector if increased speed is sought. Furthermore, the hip thrust exercise produces a powerful hypertrophy stimulus for the gluteal muscles, and cross sectional area is linked to increased strength and power potential.

3.1.4 Exercise Technique

In this section, the coaching cues for the hip thrust are outlined:

- Begin the exercise by sitting on the ground and straightening the legs (Figure 3.1.1). Line up the upper back across a secured and padded bench, step, or box. The placement of the upper back across the bench should be slightly lower than the low-bar position used in the powerlifting-style squat. Position the barbell over the lower legs. (Note: Bodyweight resistance must be mastered prior to using barbell loading, and gradually progressive increments should be utilized to prepare the body's tissues for the new movement pattern).



Figure 3.1.1. How to begin the setup of the hip thrust.

- Lean forward and grab the barbell (Figure 3.1.2).



Figure 3.1.2. Demonstration of how to grab the barbell.

- Assuming large plates are used for resistance, such as 45 lb or 20 kg plates, it is usually possible to simply roll the barbell over the thighs toward the hips.

Individuals with extremely muscular thighs may find this task challenging, in which case they'll need to make modifications such as asking a spotter to lift up on one side of the barbell to allow the exerciser to slide his or her legs underneath (Figure 3.1.3).



Figure 3.1.3. The bar is to be pulled over the thighs, toward the hips.

- Since the hip thrust puts considerable pressure across the lower abdominal and pubic region, it is wise to pad the barbell. Coaches have used Hampton thick bar pads™, Airex pads™, regular bar pads, towels, and home-made devices consisting of sagittally cut PVC pipe and hollowed out foam rollers. The thicker the padding, the better. The barbell is placed at the crease of the hips slightly above the pelvis, and precautions are taken to ensure that the bar won't slip through the padding by making sure that the slit in the pad is facing upward.

- Lean back and resume the proper upper back placement. Tighten everything up by scooting the feet towards the buttocks and "digging into" the bench and ground. The feet should be positioned around shoulder width apart and placed at a distance that creates a 90° angle at the knee joint with a vertical tibia relative to the ground at the top portion of the movement (Figure 3.1.4).



Figure 3.1.4. Flex the knees to 90°.

- From this starting position, a big breath is taken and the core is braced. (Figure 3.1.5)



Figure 3.1.5. Brace for the lift.

- Raise the barbell off the ground via a powerful contraction of the hip extensors. It is of utmost importance to ensure that the spine stays in a relatively neutral position (a slight arch is fine but excessive lumbar hyperextension can predispose the posterior elements of the spine to injury) and the extension movement comes from the hips, not the spine. Proper form involves the athlete controlling the barbell throughout the entire movement including the concentric, isometric, and eccentric portions. The knees should track directly over the toes and not cave inward. The back hinges across the bench, and any sliding of the back up and down the bench is kept to a minimum. The exerciser should keep the feet flat and push through the entire foot. Alternatively, the exerciser may dorsiflex the ankles throughout the movement in order to ensure force transfer through the heels, which may slightly increase posterior chain recruitment. For maximum safety, the head and neck should track accordingly in order to remain in alignment with the spine.

- Raise the hips until the torso is parallel with the ground and a hips-neutral position is reached. The exerciser may choose to take the exercise a couple of inches higher into hip hyperextension via a powerful contraction of the gluteals, as the hips can hyperextend around 10° with bent legs (Figure 3.1.6).



Figure 3.1.6. Extend the hips, thrusting the bar upward.

- Hold the lockout position of the exercise for a brief moment. The eccentric portion is performed under control and the barbell should lightly return to the ground. This practice may allow for better transfer to running through decreased braking forces.

3.1.5 Set Strategies

Five main strategies can be employed for the hip thrust exercise:

1. The barbell is raised concentrically for a one-count, held isometrically up top for a one-count, lowered eccentrically for a one-count, and then the barbell rests on the ground for a brief moment before repeating. This is standard technique.

2. The barbell is raised concentrically for a one-count, held isometrically up top for a three-count, lowered eccentrically for a one-count, and then repeated just prior to the barbell touching the ground. This is the constant-tension method and creates an extreme cellular swelling and occlusion effect which may maximize hypertrophic signals.
3. The barbell is raised concentrically for a one-count, held isometrically up top for a one-count, lowered eccentrically for a one-count, and then the barbell rests on the ground for three to five seconds. This is known as the rest-pause method and creates an extreme high-threshold motor unit activation stimulus which may maximize neurological adaptation.
4. The exercise is first performed via the constant tension method, and when it is no longer possible to perform any more repetitions, the exerciser switches to the rest-pause method in order to squeeze out 1-5 more repetitions. This is known as the extended set method, and since it is an advanced technique, fewer sets in this manner should be performed (one all-out set would serve the exerciser just fine).
5. The exercise is performed via a combination of barbell, plate, and band resistance. Bands can be secured to the end of the bar and fastened to heavy dumbbells residing directly underneath the bar.

3.1.6 Sets/Repetitions/Rest

- Beginners should perform 1-3 sets with 8-12 repetitions with 60-120 seconds in between sets.
- Intermediates should perform 3-4 sets with 5-8 repetitions with 60-120 seconds in between sets.
- Advanced lifters should perform 3-5 sets with 1-6 repetitions with 120 seconds in between sets.

3.1.7 Load

- Beginners should demonstrate proficiency with bodyweight resistance prior to utilizing additional loading. This means feeling the bulk of the exercise working the gluteal muscles and not the erector spinae, hamstrings, or quadriceps, and keeping a stable spine while extending the hips through a full range of motion.
- Intermediates should begin working their way up to loading equal to their own bodyweight via gradual progressions in 20-25 lb increments.
- Advanced athletes have been known to work their way up to impressive loads in the hip thrust exercise. It is not uncommon for strong and powerful athletes to use 500-600 lbs of resistance on this exercise after several months of progression. The gluteal muscles are extremely powerful and are capable of moving some serious weight from this direction in this position.

3.2 ARE ALL HIP EXTENSION EXERCISES CREATED EQUAL?

Bret Contreras, John Cronin, Brad Schoenfeld, Roy Nates, Gul Tiryaki-Sonmez

Strength & Conditioning Journal
35(2), 17-22

(Appendix 3b)

3.2.0 Summary

Many strength and conditioning coaches utilize targeted hip extension exercises to develop strength, power and endurance in the hip extensors of their athletes. Some examples include the good morning, the 45° back extension, and the horizontal back extension. Although these exercises seem to have a similar motor pattern, biomechanically, the instantaneous hip extension moment requisites at different points of range of motion vary depending on the position of the body in space. The good morning maximizes hip torque in a 90° hips-flexed position and the horizontal back extension maximizes hip torque in a 0° hips-extended position, whereas the 45° back extension maximizes both hip torque in a 45° hips-flexed position as well as average hip torque throughout the entire range of motion. For these reasons it is proposed that: one, hip extension exercises might transfer better to sport actions where the region of force accentuation is most specific; two, hip extension exercises may lead to unique structural adaptations; and three, a variety of hip extension exercises may be necessary to maximize hip extension strength and power throughout the entire range of motion.

3.2.1 Introduction

The muscles of the posterior chain, especially the hip extensors, are highly important in maximum speed and power production during activities such as sprinting and jumping (Belli et al., 2002; Blazevich, 2000; Pandy & Zajac, 1991; Schache et al., 2011). For this reason, squat, Olympic lift, deadlift, and lunge variations are considered staple exercises in a strength and conditioning practitioner's program, and targeted hip extension exercises often fall into a strength coach's top five most important exercises (Duehring, Feldmann, & Ebben, 2009; Ebben & Blackard, 2001; Ebben, Carroll, & Simenz, 2004; Ebben, Hintz, & Simenz, 2005; Simenz, Dugan, & Ebben, 2005). Three targeted hip extension exercises commonly performed in athletic weight rooms are the good morning, the 45° back extension, and the horizontal back extension. Each of these exercises can be classified as hip dominant lifts, as they act primarily on the hip joint as long as the performance of the three exercises involves flexing and extending the hips while keeping the spine and pelvis in relatively neutral positions. Since the knees do not bend substantially during each of these movements, they could be classified as straight leg hip extension exercises.

Given the similarity in movement patterns, it would seem that the aforementioned hip extension exercises are interchangeable. In other words, strength and conditioning practitioners would typically assume that there is little difference in the performance and imposed training adaptations between the three exercises. However, a biomechanical analysis of these variations has not yet been conducted in the literature, making any inferences as to their interchangeability speculative at best.

It is of utmost importance for strength coaches to design programs that transfer to sports performance, and one such way of attempting to maximize transfer of training is to utilize the principle of dynamic correspondence. Siff (2003) described dynamic correspondence as “how closely the means of special [sport-specific] strength

preparation corresponds to the functioning of the neuromuscular system in a given sport”. One of the principles of dynamic correspondence is the accentuated region of force production. If it were shown that the direction of the human body relative to space led to varying accentuated regions of force production in the good morning, the 45° back extension, and the horizontal back extension, a case could be made that the different hip extension exercises are better suited to transfer more toward particular sport actions and lead to unique structural adaptations. Moreover, combining these exercises in a training program might have a synergistic effect for sports that require high levels of force production at different hip angles.

3.2.2 Biomechanical Analysis of Selected Hip Extension Exercises

Basic physics can be used to facilitate a better understanding of the hip biomechanics in each of the three straight leg hip extension exercises, whereby instantaneous external torque is calculated at 90° hips-flexed positions (think of a standing person bent over so that the torso is parallel to the ground and the torso forms a right angle with the legs), 135° hips-flexed positions (think of a halfway position between being bent over and standing straight up), and 180° hips-neutral positions (think of a person standing straight up so that his torso and legs form a straight line). See Figure 3.2.1 for a visual representation. To illustrate these calculations, we employed a hypothetical, athletic reference individual (an athletic individual will likely store a greater proportion of his torso mass in the upper torso compared to a sedentary individual) and made a number of assumptions, including:

1. The spine and pelvis stay locked in neutral positions while the entire movement occurs at the hips.
2. The hips flex to 90°, which would require good levels of hamstring flexibility.
3. The knees stay relatively straight in each variation.

4. The good morning exercise doesn't involve any "sitting back" or knee flexion, which isn't truly representative of how the movement actually occurs. This allows for simpler calculation while not drastically altering the external hip torque measurement.
5. The head, arms, and trunk (HAT) comprise 68% of the individual's bodyweight (Tanimoto et al., 2008).
6. The average center of mass of the HAT is located 0.400 m from the hips.
7. The arm position is in a similar position in all three exercises so that the HAT center of mass is unaffected.
8. The individual is 6 ft (182 cm) tall and weighs 194 lbs (88.0 kg).
9. Each movement is performed slowly to eliminate the effects of momentum, which may not be truly representative of how the movements really occur.
10. The average center of mass of the additional load is located 0.550 m from the hips.
11. The additional load used in each exercise is 100 lbs (45.4kg).

Simplifying biomechanical calculations in this way enhances our understanding of the mechanical advantages of the three different hip extension exercises discussed in this article, helping to guide the practitioner as to their application in program design. It should be noted, however, that the aforementioned assumptions could somewhat skew the precise mechanical advantage during actual performance. In regards to the effects of momentum on hip extension torque, Lander, Simonton, and Giacobbe (1990) found that joint moments varied less than 1% between quasi-static (loading where the inertial effects are negligible) and dynamic analyses during the squat exercise with near maximum loads due to the inherent slow velocities and accelerations. Though 100 lbs would not necessarily represent maximal loading and thus would not allow for the use of quasi-static models, it provides a simple means of predicting torque angle curves at

the hips during hip extension exercises at different body positions. Figure 3.2.1 depicts the exercise positions analyzed.



Figure 3.2.1. 90, 135, and 180° of hip extension in the good morning, 45° back extension, and horizontal back extension exercises.

Calculations

Each exercise position required the calculation of two moments: the moment of the HAT acting on the hip joint and the moment of the 100 lb (45.4 kg) external resistance acting on the hip joint. Figure 3.2.2 illustrates a sample calculation. The calculations are derived as follows:

1. Calculate the weight of the HAT by multiplying the individual's bodyweight by 0.680 (68.0%)
2. Convert the weight of the HAT to Newtons by multiplying the weight in kilograms by 9.80 (which is the gravity of Earth, measured in meters per second squared).

3. Calculate the external torque of the HAT acting on the hip by multiplying the weight of the HAT (in Newtons) by the perpendicular distance from the hip to the HAT center of mass.
4. Convert the weight of the free weight implement to newtons by multiplying the weight in kilograms by 9.80 (which is the gravity of Earth, measured in meters per second squared).
5. Calculate the external torque of the free weight load acting on the hip by multiplying the weight of the implement (in Newtons) by the perpendicular distance from the hip to the implement center of mass.
6. Add the two external torques together.

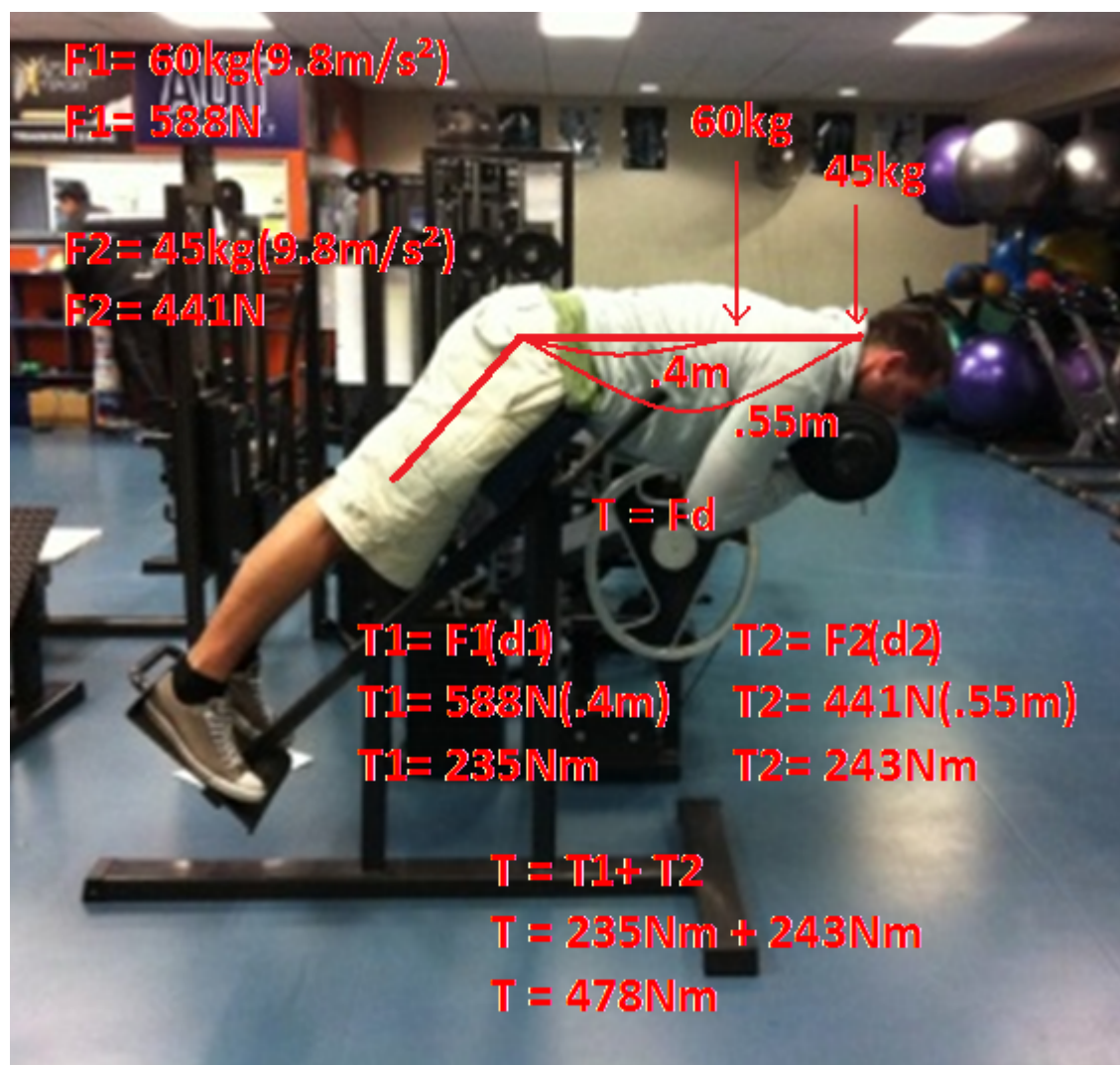


Figure 3.2.2. Sample calculation for 45° back extension exercise at a hip position of 135°

The nine different calculations are summarized in Table 3.2.1, with the precise calculations of hip torque provided for the various straight leg hip extension exercises. Note the relationship between the various positions in the hip extension exercises. Given maximum instantaneous hip torque (X), the top row shows X , $0.707X$, 0 , the middle row shows $0.707X$, X , $0.707X$, and the bottom row shows 0 , $0.707X$, X .

Table 3.2.1: Instantaneous hip extension torque at selected ranges in three different straight-leg hip-extension exercises

Exercise	Instantaneous Hip Torque at 90°	Instantaneous Hip Torque at 135°	Instantaneous Hip Torque at 180°
Good Morning	478 N·m	338 N·m	0.00 N·m
45° Back Extension	338 N·m	478 N·m	338 N·m
Horizontal Back Extension	0.00 N·m	338 N·m	478 N·m

3.2.3 Practical Applications

As is evident from the previously described calculations, hip torque varies considerably throughout hip extension range of motion depending on the position of the upper body relative to the axis of rotation, i.e., hip joint. During the good morning, hip torque is highest (i.e., 478 N·m) in a 90° hips flexed position and diminishes throughout the concentric portion of the repetition, reaching its lowest value (i.e., 0 N·m) in a hips extended position (i.e., 180° or fully extended). In the case of the 45° back extension, hip torque is highest (i.e., 478 N·m) in a 135° mid range hip position and the hip torque is more consistent throughout the range of motion, never dropping below 338 N·m. The horizontal back extension creates very little hip torque in a hips-flexed position (i.e., 0 at 90° of hip flexion) but increases steadily throughout the concentric portion of the repetition, reaching its apex (i.e., 478 N·m) when the hips are fully extended (see Figure 3.2.3).

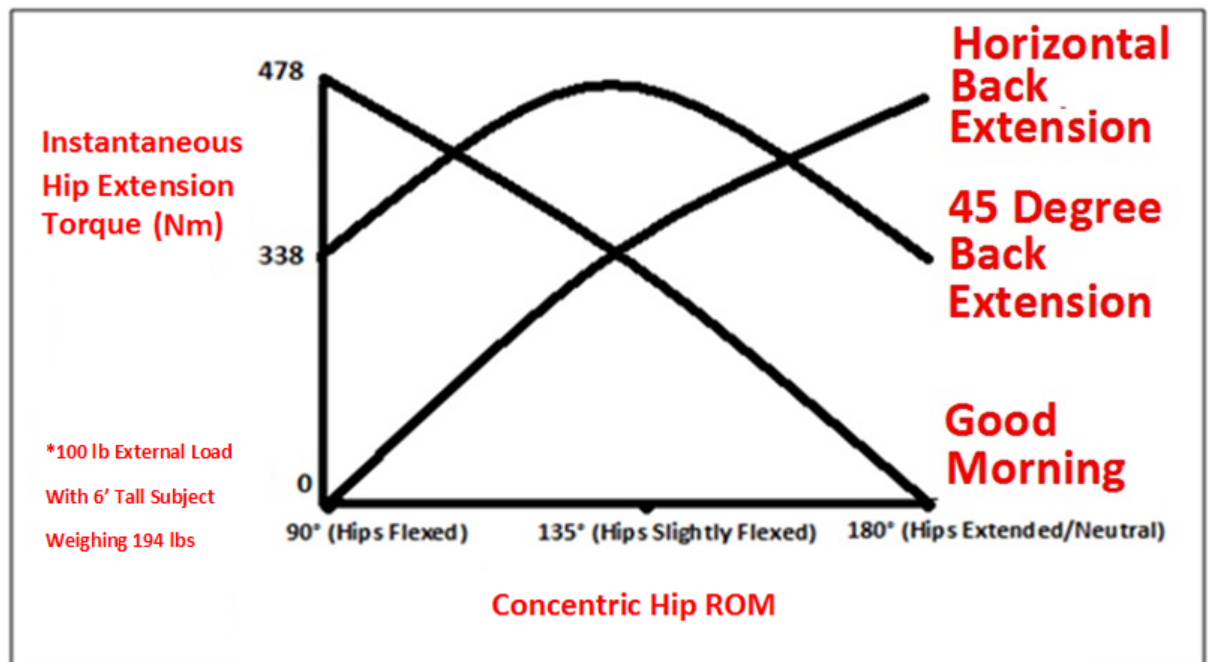


Figure 3.2.3. Graph of instantaneous hip torque at selected ranges of motion in three different hip extension exercises.

In order to overcome inertia of the system (barbell plus body mass), hip extensor muscle force (passive and active) must exceed the torques shown in the different positions that can be observed in Figure 3.2.3 since internal forces must be greater than external forces in order for concentric movement to occur. Granted, athletes often perform these movements explosively, but with higher percentages of one-rep maxes, the effects of momentum are minimized, enabling a suitable model for analysis.

Since a definition in the literature is lacking, one could refer to single joint exercises that create maximum torque while the prime movers are stretched as long length accentuated force exercises. Conversely, one could refer to single joint exercises that create maximum torque while the prime movers are shortened as short length accentuated force exercises. Exercises that create maximum torque while the prime movers are between either extreme would be considered mid length accentuated force exercises. Using our hip extension exercises as examples, the good morning exercise would be considered a long length accentuated force exercise, the horizontal back extension exercise would be considered a short length accentuated force exercise, and

the 45° back extension exercise would be classified as a mid length accentuated force exercise.

This language works well with monoarticular muscles but is tricky with biarticular muscles. For example, consider the hip extension exercises discussed herein. During straight leg hip extension, the gluteus maximus, a monoarticular muscle, is in a long length position with hips flexed and a short-length position with hips extended. However, although the hamstrings, a biarticular muscle, shorten as the hips extend, they could be markedly shorter if the knees are flexed. By examining Figure 3.2.3, it appears that long length accentuated force exercises have ascending strength curves and descending torque-angle curves, mid length accentuated force exercises have U-shaped strength curves and upside-down U-shaped torque-angle curves, and short length accentuated force exercises have descending strength curves and ascending torque-angle curves. Moreover, this language is better suited for single-joint movements compared to multi-joint movements, as when adjacent joints move simultaneously, the lengthening of a muscle can be diminished or enhanced. For example, the biarticular hamstrings do not undergo much length change during performance of the squat given their dual role as knee flexors and hip extensors (Schoenfeld, 2010a); when one joint is lengthening, the other is shortening.

If attempting to maximize carryover to sport action, it may be wise to select the exercise that most appropriately mimics the hip torque curve involved in the action. For example, since the good morning maximizes hip torque in a flexed position, it may transfer better to the glute functioning involved during the late swing phase of sprinting because it maximizes hip torque in a flexed position, whereas the horizontal back extension may transfer better to the glute function involved during the stance phase of sprinting because it maximizes hip torque in an extended position. The 45° back extension may be best suited to the acceleration phase of sprinting due to the

maximization of hip torque in the middle range of the hip flexion-extension axis, which is more closely associated to the region of ground contact involved in the first few seconds of a sprint.

At ground contact in maximal speed sprinting, the glutes are at short lengths while the hamstrings are at long lengths. Gittoes and Wilson (2010) showed that the hip and knee angles from touchdown to toe-off during maximal speed sprinting were approximately 150 to 175° and 155 to 145°, respectively. It would therefore make sense to strengthen these muscles at their corresponding lengths when attempting to maximize carryover, especially considering that exercise has been noted to influence the optimal length of a muscle (Brughelli et al., 2010). This could be coined “torque-angle specificity” or “force-ROM specificity”. However, contradictory research has recently emerged in this particular area. Clark, Humphries, Hohmann, and Bryant (2011) showed that bench press training at a variety of ranges of motion and muscle lengths yielded greater benefits when compared to full range of motion bench in terms of mid-range reactive strength and end-range force production during isokinetic testing while not impairing initial-range performance. Yet Hartmann et al. (2012) showed that although partial squats yielded superior results in terms of end-range strength production compared to full range squats, partial squat training led to inferior results in terms of jumping performance, maximum voluntary contraction, and rate of force development, and diminished initial-range squat performance. Further research is needed to elucidate these apparent contradictions.

Regarding hypertrophic adaptations, it has been proposed that the three primary mechanisms leading to muscular growth are mechanical tension, muscular damage, and metabolic stress (Schoenfeld, 2010b). With respect to mechanical tension, exercises create varying amounts of external torque throughout a joint’s range of motion (see Figure 3.2.3). Anecdotally, exercises that produce high torques at long muscle lengths

tend to create the most delayed onset muscle soreness, most likely due to the damage of the stretched sarcomeres (e.g., flies and the pectorals, lunges and the glutes, good mornings and the hamstrings), which theoretically could enhance hypertrophy due to the muscular damage incurred (Schoenfeld, 2012). In addition, anecdotally, exercises that produce high torques at mid-range and shorter muscle lengths tend to create the most metabolic stress. For example, some exercises are well known for creating a “pump” effect (e.g., cable crossovers and the pecs, hip thrusts and the glutes, seated band leg curls and the hamstrings), better known to researchers as cell swelling, which has been proposed to enhance hypertrophy (Schoenfeld, 2010a). Furthermore, exercises that keep consistent torque on the targeted joint, such as the 45° hyperextension, would theoretically occlude the most blood flow and lead to the most hypoxia, which has been proposed to enhance muscular hypertrophy through mechanisms involving metabolic stress (Tanimoto et al., 2008). These hypotheses warrant further investigation.

Muscle damage associated with eccentric training can lead to sarcomerogenesis through two different proposed mechanisms (Carlsson, Yu, Moza, Carpen, & Thornell, 2007), and it stands to reason that eccentrics with accentuated force production at long lengths would lead to increases in sarcomeres in series, thereby increasing muscle length. These adaptations can improve athletic performance by increasing contractile velocity and power (Butterfield, Leonard, & Herzog, 2005). Furthermore, since the protein titin is proposed to contribute considerably to passive muscle force when a muscle is actively stretched to long lengths (Leonard & Herzog, 2010; Nishikawa et al., 2012), one could speculate that long-length accentuated force exercises do a better job of creating passive tissue adaptations than do short-length accentuated force exercises, which could be beneficial for elastic strength. Strength and power athletes have been shown to possess unique titin adaptations compared to controls (McBride, Triplett-

McBride, Davie, Abernethy, & Newton, 2003) and targeted long-length training could potentially enhance such effects.

By examining Figure 3.2.3, since short-length accentuated force exercises require a “ramping up” of muscle force throughout the concentric range of motion, they might be better suited for accelerative purposes than long-length accentuated force exercises. This is because muscle force diminishes during long-length accentuated force exercises throughout the concentric range of motion. However, considering that isometric training at longer muscle lengths has been shown to increase tendon stiffness and MVC throughout the entire range of motion, the same which cannot be said of isometric training at shorter lengths, an argument could be made that long-length accentuated force exercises are superior to short-length accentuated force exercises in terms of tendon and MVC adaptations (Kubo et al., 2006). However, this would require taking a big leap in logic, as training effects from isometric exercises do not necessarily match those of dynamic exercises. Cavagna (2006) showed that the work performed by the contractile components decreases with increasing speed due to a greater proportion of the length change taken up by the tendons as well as decreasing force owing to the force-velocity relationship, implying that range-specific isometric muscle force coupled with elastically-efficient tendons is a characteristic of high velocity sprinting and that concentric power is more important during acceleration sprinting.

Based on the calculated external torques, it is apparent that relatively light external loads (i.e., 100 lbs) can be used during straight-leg hip extension exercises to create considerable peak hip extension torque (i.e., 478 N·m) owing to long resistance moment arms. For comparative purposes, Escamilla, Fleisig, Lowry, et al. (2001) showed that powerlifters with an average body weight of 201 lbs and an average maximal squat of 497 lbs imposed 628 N·m of peak hip extension torque during the squat exercise, and (Escamilla et al., 2000) reported that powerlifters with an average

body weight of 169 lbs and an average maximal deadlift of 489 lbs imposed 599 N·m of peak hip extension torque during the deadlift exercise. Clearly, the squat and deadlift allow for heavier loads, but due to their shorter resistance moment arms, they do not dramatically exceed the hip extension torques required of straight-leg hip extension movements since the longer resistance moment arms counteract the effects of the lighter loads. It should be noted, however, that the authors only analyzed the hip joint and not the external torques at the ankle, knee, or spine. Thus, training angle is an important consideration with respect to exercise selection in program design.

3.2.4 Conclusion

All hip extension exercises are not created equal. External torque varies depending on the position of the human body relative to the ground. Standing hip extension exercises exhibit their highest instantaneous torque when bent forward to 90°. Hip extension exercises performed at a 45° angle have more consistent levels of instantaneous torque throughout the movement. Horizontal hip extension exercises exhibit their highest level of instantaneous torque when the hips are extended. One can logically conclude from this brief treatise that multiple hip extension exercises should be performed for maximum balance of hip strength throughout the entire hip extension range of motion. Furthermore, it may be that athletes should be assessed over the entire range of motion to determine strength deficits, which in turn should result in better strength diagnosis and individualized programs. Finally, the strength and conditioning practitioner needs a higher order understanding of exercise and accentuated moment requisites in relation to the activity or event of interest. That is, for optimal transference from the strength and conditioning facility to the competitive environment (dynamic correspondence), careful consideration needs to be given to exercise choice.

Future research should be conducted involving 3D motion capture, force plate, and EMG to calculate real life hip extension moments. Furthermore, future research should be conducted to determine if the various hip extension exercises do, in fact, lead to unique structural adaptations and carryover to functional activities such as running and jumping.

***A COMPARISON OF TWO GLUTEUS MAXIMUS EMG MAXIMUM
VOLUNTARY ISOMETRIC CONTRACTION POSITIONS***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**PeerJ
3, e1261**

(Appendix 3d)

4.0 Prelude

When conducting electromyography (EMG) research, it is important to normalize data to a maximum voluntary isometric contraction (MVIC) position. There is currently a paucity of research comparing different MVIC positions for the gluteus maximus. Since many MVIC positions for the gluteus maximus are used in the literature, it is unclear as to which position to use when conducting EMG research. If it is shown that one position is superior to another, then that MVIC position will be used in upcoming Chapters 6 to 8. This chapter will seek to compare the most common MVIC position for the gluteus maximus with a novel position that showed favorable results when collecting pilot data. The results of this study will provide the MVIC position that will be used in the ensuing EMG studies.

4.1 Introduction

MVICs are often used to normalize EMG signals. It is important to employ an MVIC position that elicits the highest activation in order to increase the validity of EMG studies and decrease incidents of abnormally high normalized mean and peak EMG data. In order for accurate comparisons to be made between studies, it is also important for researchers to standardize MVIC positions or at least use positions that elicit similar magnitudes of EMG activity. A number of MVIC positions have been used in the literature to assess the gluteus maximus, including the Biering-Sorenson position (Cambridge, Sidorkewicz, Ikeda, & McGill, 2012; McGill et al., 2009), the prone straight leg hip extension position (Barton et al., 2014; Worrell et al., 2001), the prone bent-leg position (Jakobsen et al., 2013; Youdas et al., 2013), the prone straight leg position with 70° of hip flexion (Simenz et al., 2012), and the standing bent-leg position (Boudreau et al., 2009). The most commonly used position, however, is the prone bent-leg (90°) hip extension with manual resistance applied to the distal thigh (PRONE)

(Choi et al., 2014; Emami, Arab, & Ghamkhar, 2014; Hislop, Avers, & Brown, 2013; Kang et al., 2013; Kendall, McCreary, Provance, Rodgers, & Romani, 1993; Oh et al., 2007).

A recent study by Simenz et al. (2012) that used a prone gluteus maximus MVIC position in 70° of hip flexion demonstrated the importance of standardizing MVIC positions across studies. Researchers have shown that the gluteus maximus is activated to a much smaller degree at higher degrees of hip flexion and reaches a maximum at end-range hip extension (Worrell et al., 2001). By employing an MVIC position that renders significantly lower EMG activity than those values that are truly maximal, the normalized data of Simenz et al. (2012) are most likely overestimated. For example, if the work of Worrell et al. (2001) is extrapolated, the MVIC position used by Simenz would only elicit approximately 80% of true MVIC, translating into 25% greater mean and peak values when compared to the true MVIC position. The data reported by Simenz et al. (2012) therefore cannot be used for comparison with exercises in other studies that utilized alternative MVIC positions with smaller hip flexion angles, as the data would have overestimated how effectively the gluteus maximus was activated. Therefore, it is apparent that researchers should only compare EMG data that utilize positions that render similar values.

Since Worrell et al. (2001) found that full hip extension elicited the greatest amount of gluteus maximus EMG activity, which is corroborated by earlier work from Wheatley and Jahnke (1951) and Fischer and Houtz (1968), it is postulated that the most appropriate gluteus maximus MVIC position is at full hip extension or hip hyperextension. PRONE is currently the recommended position in several texts on muscle testing (Hislop et al., 2013; Kendall et al., 1993), although to the authors' knowledge, this position has not been compared to others in the literature. In order to correct for individual variation, some researchers have employed multiple MVIC

positions. For example, McGill et al. (2009) used both the Biering-Sorenson and PRONE positions, and whichever position elicited the greatest activity was used for normalization purposes. The authors, however, are unaware of any existing research that quantitatively compares gluteus maximus MVIC positions.

The gluteus maximus muscle appears to be segmented into at least two subdivisions which may display different EMG activity in response to certain muscle actions. McAndrew et al. (2006) used a laser-based mechanomyographic (MMG) technique to measure the mean contraction time in six subdivisions of the gluteus maximus,, both in the sagittal plane (superior, middle, inferior) and in the frontal plane (medial and lateral). The superior region displayed the longest contraction time followed by the middle region and then the inferior region. On the basis of these findings, McAndrew et al. (2006) suggested that the superior region may contain more slow twitch fibers and be more involved in postural tasks compared to the inferior region, while the inferior region may contain more fast twitch fibers and be more involved in dynamic tasks. This is further substantiated by the work of Lyons, Perry, Gronley, Barnes, and Antonelli (1983) and Karlsson and Jonsson (1965), who found differences between upper (UGM) and lower (LGM) gluteus maximus EMG during functional movement; for example, load acceptance during stair ambulation better targets the LGM (Lyons et al., 1983), while hip abduction better targets the UGM (Karlsson & Jonsson, 1965).

Pilot data from our lab showed that some subjects were able to elicit greater EMG activity during a standing glute squeeze (SQUEEZE) when compared to PRONE, and this was especially true for the UGM. Given this observation and the findings articulated in previous paragraphs, the purpose of this investigation was to compare UGM and LGM EMG activity in PRONE versus SQUEEZE. Based on our pilot data, it

was hypothesized that SQUEEZE would elicit greater UGM EMG activity, while PRONE would elicit greater LGM EMG activity.

4.2 Methods

A convenience sample of thirteen healthy women (age = 28.9 ± 5.1 years; height = 164 ± 6.3 cm; body mass = 58.2 ± 6.4 kg) with 7.0 ± 5.8 years of resistance training experience participated in this study. Inclusion criteria required subjects to be between 20 to 40 years of age and have at least three years of consistent resistance training experience. All subjects were healthy and free of any musculoskeletal or neuromuscular injuries, pain, or illnesses. Subjects completed an Informed Consent form. Subjects were advised to refrain from training their lower body for 72 hours prior to testing. The study was approved by the Auckland University of Technology Ethics Committee.

4.2.1 Procedures

Subjects first performed a 10-minute general warm-up consisting of various dynamic stretches for the lower body musculature. Following warm-up, subjects practiced each testing position several times until they felt comfortable with the technique. Subjects were asked to wear appropriate clothing for access to the EMG electrode placement sites. Before placing the electrodes on the skin, excess hair was removed with a razor, and skin was cleaned and abraded using an alcohol swab. After preparation, self-adhesive disposable silver/silver chloride pre-gelled dual snap surface bipolar electrodes (Noraxon Product #272, Noraxon USA Inc, Scottsdale, AZ) with a diameter of 1 cm and an inter-electrode distance of 2 cm were attached in parallel to the fibers of the right UGM and LGM, in concordance with the recommendations of Hermens et al. (1999) and Lyons et al. (1983). After the electrodes were secured, a quality check was performed to ensure EMG signal validity.

Following electrode placement, subjects completed three trials of PRONE (Figure 4.1) then SQUEEZE (Figure 4.2) or vice versa. For example, if a subject was randomized to complete PRONE first, her testing order would be PRONE, SQUEEZE, rest, PRONE, SQUEEZE, rest, PRONE, SQUEEZE. Each rest phase consisted of three minutes of rest. Randomization was counterbalanced so that half the subjects performed PRONE first and the other half performed SQUEEZE first. In all MVIC positions, subjects were instructed to contract the gluteus maximus “as hard as possible”.



Figure 4.1 Prone bent-leg hip extension against manual resistance maximum voluntary isometric contraction position.



Figure 4.2 Standing glute squeeze maximum voluntary isometric contraction position.

Raw EMG signals were collected at 2000 Hz by a Myotrace 400 EMG unit (Noraxon USA Inc, Scottsdale, AZ). Data was sent in real time to a computer via Bluetooth and recorded and analyzed by MyoResearch 3.6 Clinical Applications software (Noraxon USA Inc., Scottsdale, AZ). A 10-500 Hz bandpass filter was applied

to EMG data. Signals of all MVIC trials were full-wave rectified and smoothed with a root mean square (RMS) algorithm with a 100 ms window. Maximal peak EMG values over a 1000 ms window were then used to normalize peak EMG signals obtained during each MVIC trial (Vera-Garcia, Moreside, & McGill, 2010).

4.2.2 Statistical Analysis

Paired samples *t*-tests were performed using Stata 13 (StataCorp LP, College Station, TX). Alpha was set a priori at 0.05 for significance. Effect sizes (ES) were calculated by Cohen's *d* using the formula $M_1 - M_2 / SD$, where means (M) from each group (PRONE and SQUEEZE) were subtracted and divided by the pooled standard deviation (SD). ES were defined as small (0.2), moderate (0.5), and large (0.8) (Cohen, 1988). Confidence intervals (95% CI) for each ES were also calculated.

4.3 Results

The normalized peak EMG for the different exercises and gluteus maximus sections can be observed in Table 4.1. In terms of the UGM comparison, no significant differences were observed in the peak EMG for both exercises (ES = 0.009; 95% CI = -0.760 – 0.777; *p* = 0.986). With regards to the LGM, a moderate ES was observed (0.716; 95% CI = -0.116 – 1.52) between the two exercises. However, this was found to be non-significant (*p* = 0.164) EMG activity between PRONE and SQUEEZE (Table 4.1, Figure 4.2).

Table 4.1. Group mean \pm SD of normalized peak EMG amplitudes.

	PRONE	SQUEEZE
UGM	91.9 \pm 11.6	92.0 \pm 11.3
LGM	94.5 \pm 13.6	85.1 \pm 12.6

UGM = upper gluteus maximus; LGM = lower gluteus maximus

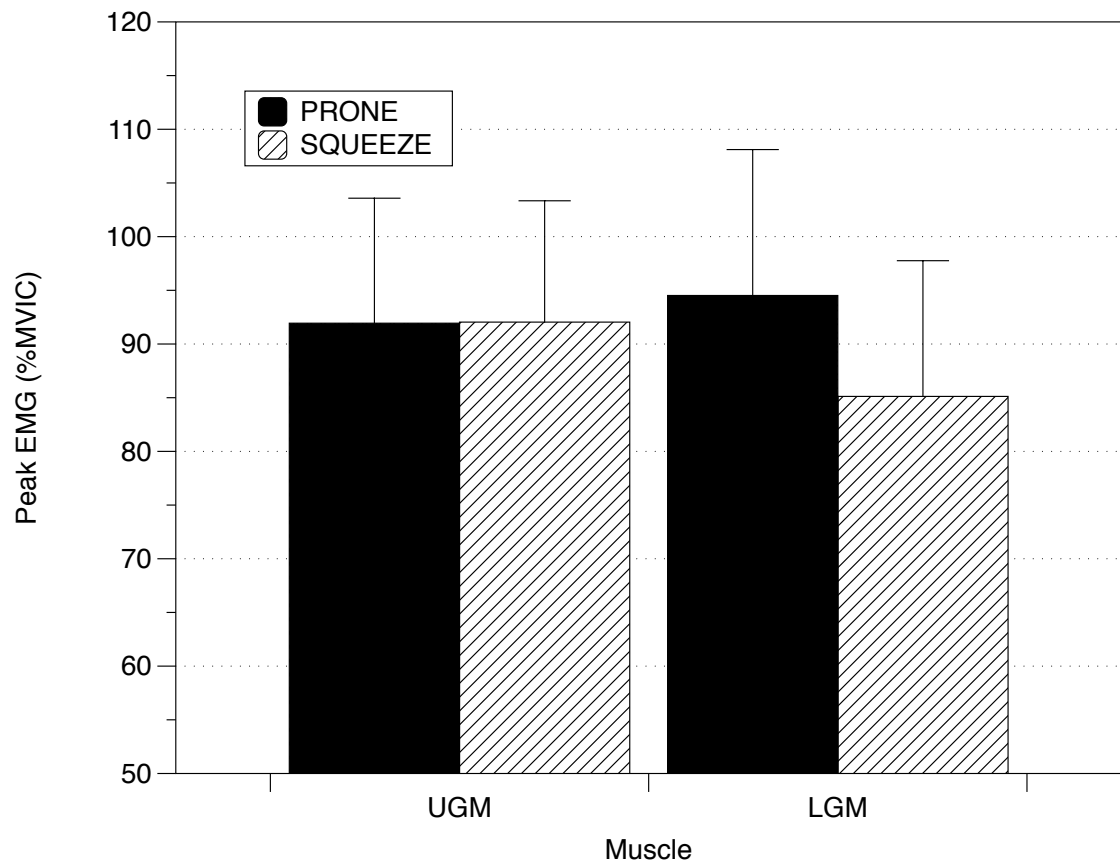


Figure 4.2 Group mean \pm SD of normalized peak EMG amplitudes
UGM = upper gluteus maximus; LGM = lower gluteus maximus

4.4 Discussion

The purpose of this investigation was to compare a novel gluteus maximus MVIC position, SQUEEZE, to the current gold standard, PRONE. Our hypotheses were rejected as there were no statistically significant differences between the two positions tested (Table 4.1, Figure 4.1). However, despite no statistically significant differences, the peak EMG values for the LGM were approximately 9% higher for the PRONE compared to the SQUEEZE. Consequently, if the SQUEEZE test were used for normalization, it would render approximately 10% higher mean and peak EMG values compared to the PRONE test. Therefore, although not statistically significant, the findings could be considered practically meaningful. Furthermore, these data show a large amount of individual variation (Table 4.2), which has been previously described by McGill (1990) and Vera-Garcia et al. (2010) for other muscles.

Table 4.2. Number of subjects (percentage of subjects (%)) to achieve maximal activation in each MVIC technique.

	PRONE	SQUEEZE
UGM	7 (53.9)	6 (46.2)
LGM	10 (76.9)	3 (23.1)

UGM = upper gluteus maximus; LGM = lower gluteus maximus

There are several kinematic and kinetic differences between PRONE and SQUEEZE, any of which may have affected our results, either individually or in combination. During PRONE, the knee is bent to 90°, whereas during SQUEEZE, the knees are fully extended. Previous research has shown that gluteus maximus EMG activity during hip extension is greater with the knees flexed than when extended, presumably resulting from a greater reliance upon the gluteus maximus for hip extension due to decreased hamstrings length (Kwon & Lee, 2013). On the other hand, extended knees allow for greater hip extension range of motion compared to flexed knees, thereby shortening the gluteal fibers to a greater extent (Van Dillen, McDonnell, Fleming, & Sahrman, 2000) and leading to a greater amount of gluteus maximus EMG activity (Worrell et al., 2001). In addition, PRONE involved primarily hip hyperextension since the pelvis was fixed, whereas SQUEEZE appeared to involve a combination of hip extension and posterior pelvic tilt. Although posterior pelvic tilt mimics hip extension (Neumann, 2010), it is unclear how each of these kinematic variables might affect gluteus maximus EMG activity individually. To the authors' knowledge, no study to date has investigated gluteus maximus EMG activity with varying combinations of hip extension and posterior pelvic tilt during MVIC actions. Moreover, PRONE is an open kinetic chain maneuver with the torso stabilized onto a bench, whereas SQUEEZE is a closed kinetic chain maneuver performed in a standing position. Stensdotter, Hodges, Mellor, Sundelin, and Hager-Ross (2003) investigated the EMG activity of the quadriceps muscle group during open kinetic chain and closed

kinetic chain positions during MVIC actions and reported significant differences in EMG amplitude. More specifically, the rectus femoris displayed greater EMG activity during open kinetic chain maneuvers (40% vs. 10%) while the vastus medialis displayed greater EMG activity during closed kinetic chain maneuvers (46% vs. 40%). It is therefore hard to predict whether the gluteus maximus would inherently display greater or lesser EMG activity during either open or closed kinetic chain maneuvers. Finally, PRONE required manual resistance, whereas SQUEEZE relied upon anatomical structures surrounding the hip to provide resistance against hip extension. Whether this factor has any effect on EMG activity recorded in a muscle is unclear, as the authors are unaware of any previous investigations into the effect of squeezing a muscle whereby range of motion is limited by anatomical structures on EMG activity rather than against external resistance.

This investigation was subject to several important limitations. First, although we observed what may have been a practically important difference between the MVIC positions, this difference was not found to be statistically significant, which suggests that our initial estimates for the appropriate sample size may have been too small. Second, there were several kinematic differences between the two positions that were explored (PRONE and SQUEEZE), including different pelvic, hip, and knee joint angles. There were also kinetic differences between the two positions, in that PRONE was an open kinetic chain maneuver and SQUEEZE was a closed kinetic chain maneuver. Moreover, PRONE used external resistance and SQUEEZE utilized oppositional torques produced by internal, anatomical structures. These multiple differences make it difficult to assess whether our results arose from a combination of biomechanical factors acting in opposing directions, heterogeneity, or genuinely no difference between the conditions. Third, we only compared two MVIC positions, and it is feasible that other positions might result in superior or inferior levels of EMG

activity. Fourth, we only investigated two subdivisions of the gluteus maximus muscle and there are indications that there may be others, from proximal to distal, medial to lateral, and superficial to deep.

4.5 Conclusion

Although these data are inconclusive as to which position is superior, they do provide insight as to the complexity of MVIC positions for the gluteus maximus. More specifically, due to the large individual variations (Table 4.2), it is recommended that multiple MVIC positions be utilized to ensure that the greatest possible EMG amplitude be the divisor during normalization. These recommendations are well in line with other studies which have utilized or recommended multiple MVIC positions (McGill et al., 2009; Vera-Garcia et al., 2010). Future research should use heterogeneous samples, such as athletic males, and also test more positions, such as the Biering-Sorenson position, quadruped hip extension position, and top hip thrust position (Contreras et al., 2011), each with manual resistance, along with the tall kneeling position.

***A COMPARISON OF GLUTEUS MAXIMUS, BICEPS FEMORIS,
AND VASTUS LATERALIS EMG ACTIVITY IN THE PARALLEL,
FULL, AND FRONT SQUAT VARIATIONS***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**Journal of Applied Biomechanics
32(1), 16-22**

(Appendix 3e)

5.0 Prelude

The findings in the previous chapter instil confidence in collecting valid EMG data for the gluteus maximus when normalized to a MVIC. Chapter 10 will consist of a training study that uses a squat variation. If it is found that one squat variation elicits superior gluteus maximus EMG activity compared to other variations, then this variation will be utilized in the training study. However, if the squat variations are shown to be highly similar in muscle activation, then the variation that the subjects in Chapter 10 are most comfortable performing will be utilised. This chapter will seek to analyze the differences in EMG activity between three popular squat variations: full, parallel, and front squats. Of particular interest is gluteus maximus EMG activity.

5.1 Introduction

The squat is not only a core movement in Olympic weightlifting and powerlifting, but it is also a staple exercise for athletes and bodybuilders. Due to its applicability to functional exercise and sport, numerous variations have been developed and employed in the fields of strength and conditioning and physical therapy. Many of these squat variations have been investigated and/or compared in terms of kinetics (Escamilla, Fleisig, Lowry, et al., 2001; Escamilla et al., 1998; Gullett, Tillman, Gutierrez, & Chow, 2009; Wilk et al., 1996), kinematics (Bryanton, Kennedy, Carey, & Chiu, 2012; Escamilla, Fleisig, Lowry, et al., 2001; Gullett et al., 2009; Wretenberg, Feng, & Arborelius, 1996), muscle activation (Comfort, Pearson, & Mather, 2011; Gullett et al., 2009; Schwanbeck, Chilibeck, & Binsted, 2009; Wilk et al., 1996), hormonal response (Cook & Crewther, 2012; Jones, Ambegaonkar, Nindl, Smith, & Headley, 2012; Shaner et al., 2014), post-activation potentiation (Hanson, Leigh, & Mynark, 2007; Moir, Mergy, Witmer, & Davis, 2011; Weber, Brown, Coburn, & Zinder, 2008; Witmer, Davis, & Moir, 2010), correlations to performance (Chelly et al., 2010; Cunningham et

al., 2013; McBride et al., 2009; Wisloff, Castagna, Helgerud, Jones, & Hoff, 2004), and transfer of training (Bloomquist et al., 2013; Hartmann et al., 2012; Morrissey, Harman, Frykman, & Han, 1998; Rhea, Kenn, & Dermody, 2009). In addition, several reviews (Clark, Lambert, & Hunter, 2012; Escamilla, 2001; Hartmann, Wirth, & Klusemann, 2013; Schoenfeld, 2010b) and one meta-analysis (Seitz, Reyes, Tran, de Villarreal, & Haff, 2014) have been conducted on the squat exercise.

Like most exercise and sports medicine research, a disproportionate amount of previous research on the squat was completed on male subjects (Costello, Bieuzen, & Bleakley, 2014). To the authors' knowledge, only two studies have investigated squat electromyography (EMG) amplitude in female subjects (Gorsuch et al., 2013; Lynn & Noffal, 2012), one of which noted greater biceps femoris EMG activity in females than their male counterparts (Lynn & Noffal, 2012). Furthermore, anthropometric and kinematic differences exist between males and females during the squat, which means that squat data cannot be extrapolated between sexes (McKean & Burkett, 2012). Therefore, there is a need to fill this gender gap in the literature.

With regards to gluteus maximus EMG amplitude in the squat exercise, several important studies have been conducted. Caterisano and colleagues (Caterisano et al., 2002) investigated the effects of squat depth on gluteus maximus EMG. The investigators found that gluteus maximus EMG amplitude significantly increased with depth (35.5 vs. 28.0%). However, as noted by Clark et al. (2012), Caterisano et al. (2002) did not utilize the same relative loading at each squat depth tested, which may have affected the outcome. Paoli, Marcolin, and Petrone (2008) and McCaw and Melrose (1999) both found significant increases (0.0288 vs. 0.0205 mV and 9.40 vs. 8.30 μ V.s, respectively) in gluteus maximus EMG amplitude and integrated EMG values, respectively, with increases in squat stance width. Aspe and Swinton (2014) analyzed the back squat and the overhead squat and found that, at 90% 3 RM, the back

squat elicited significantly greater gluteus maximus EMG amplitude than the overhead squat (92.7 vs. 60.9%), in addition to significantly greater biceps femoris (71.1 vs. 54.0%) and vastus lateralis (vastus lateralis) (99.2 vs. 82.3%) amplitude.

A number of studies have compared front and back squat variations (Braidot, Brusa, Lestussi, & Parera, 2007; Comfort, Pearson, et al., 2011; Diggin et al., 2011; Gullett et al., 2009; Hartmann et al., 2012; Russell & Phillips, 1989; Stuart, Meglan, Lutz, Growney, & An, 1996; Yavuz et al., 2015; Yetter & Moir, 2008). Gullett et al. (2009) examined kinetic and EMG differences between the front and back squats and found that the back squat exhibited significantly greater knee moments (1.00 vs. 0.700 N.m/kg), but no significant differences between biceps femoris, rectus femoris, semitendinosus, vastus lateralis, vastus medialis, or erector spinae EMG amplitude were found. Intuitively, the back squat utilizes greater energy from the hips while the front squat utilizes greater energy from the knees (Braidot et al., 2007). Russell and Phillips (1989) found similar knee extensor moments, trunk extensor moments, trunk angles, and lumbar compressive and shear forces between front and back squats. Stuart et al. (1996) described similar anteroposterior shear and compressive forces at the knee, knee flexion/extension moments, and quadriceps EMG amplitude in front and back squats. In this study, hamstring EMG amplitude was found to differ significantly between the front and back squat at 90° and 60° in the ascent phase, but the authors failed to specify which exercise variation elicited greater hamstring activity. Lastly, Yavuz et al. (2015) investigated the EMG activity of the vastus lateralis, vastus medialis, rectus femoris, semitendinosus, biceps femoris, gluteus maximus, and erector spinae in front and back squats performed to 90° knee flexion. The only differences the investigators observed were greater vastus medialis EMG activity in the front squat and greater semitendinosus EMG activity during the ascending phase of the back squat.

Numerous studies have compared differences in squat depths (Bryanton et al., 2012; Caterisano et al., 2002; Cotter, Chaudhari, Jamison, & Devor, 2010; Cotter, Chaudhari, Jamison, & Devor, 2013; Drinkwater et al., 2005; Esformes & Bampouras, 2013; Gorsuch et al., 2013; Wretenberg et al., 1996). Gorsuch et al. (2013) found that parallel squats elicited significantly greater rectus femoris (0.180 vs. 0.140 mV) and erector spinae (0.160 vs. 0.130 mV) EMG amplitude than partial squats but reported that hamstring EMG amplitude was not statistically different. Bryanton et al. (2012) described an increase in knee extensor and hip extensor relative muscular effort with increases in squat depth. Both patellofemoral joint reaction forces and external knee flexion moments increased with increases in squat depth (Cotter et al., 2010; Cotter et al., 2013). Drinkwater et al. (2005) found that partial squats produced greater peak power and peak forces, but full squats produced greater peak velocities and work. Esformes and Bampouras (2013) found that in a study examining the effects of post-activation potentiation, parallel squats led to significantly greater improvements than quarter squats in countermovement jump height, peak power, impulse, and flight time (22.2–28.0%). Wretenberg et al. (1996) described greater knee moments and greater biceps femoris EMG amplitude during deep squats in comparison to parallel squats, but the two squat styles exhibited similar hip moments, rectus femoris EMG amplitude, and vastus lateralis EMG amplitude.

The front, full, and parallel squat are three common variations of the squat. The purpose of this investigation was to compare upper gluteus maximus, lower gluteus maximus, biceps femoris, and vastus lateralis EMG amplitude during 10 repetitions utilizing estimated 10 RM front, full, and parallel squat loads in resistance trained women. Previous researchers have indicated that hamstrings EMG amplitude is likely to be unaffected by depth, quadriceps EMG amplitude is likely to be increased by increasing depth, and that the effect of depth on gluteus maximus EMG amplitude is

unclear. Therefore, it is hypothesized that there would be no difference in upper gluteus maximus, lower gluteus maximus, or biceps femoris EMG amplitude between the front, full, and parallel squat, but the front and full squat would elicit greater vastus lateralis EMG amplitude than the parallel squat.

5.2 Methods

A convenience sample of thirteen experienced, resistance-trained women (age = 28.9 ± 5.1 years; height = 164 ± 6.3 cm; body mass = 58.2 ± 6.4 kg) participated in this study. Subjects had 7.00 ± 5.8 years of resistance training experience and a 10 RM of 39.2, 46.7, and 53.1 kg in the front, full and parallel squat, respectively. Inclusion criteria required subjects to be between 20 to 40 years of age, have at least three years of consistent resistance training experience, and be familiar with performance of the front, full, and parallel squat. All subjects were healthy and free of any musculoskeletal or neuromuscular injuries, pain, or illnesses. Subjects filled out an Informed Consent and Physical Activity Readiness Questionnaire (PAR-Q). Any subject that answered “yes” to any of the questions on the PAR-Q or refused to sign the Informed Consent were excluded. Subjects were advised to refrain from training their lower body for 72 hours prior to testing. To ensure acceptable performance in the three squat variations, subjects performed each movement using only a barbell while the lead researcher evaluated technique. If a subject reported pain, discomfort, or failed to perform the movement correctly, she would have been excluded from participation. If, for any reason, a subject could not complete a trial, her data would have been discarded. All recruited subjects fulfilled the inclusion criteria, and no subjects were excluded. The study was approved by the Auckland University of Technology Ethics Committee.

Subjects first performed a 10-minute general warm-up consisting of various dynamic stretches for the lower body musculature. Afterwards, three progressively

heavier specific warm-up sets were performed for the front, full, and parallel squat. Next, subjects' 10 RM in each squat variation were calculated using the methods described by Baechle and Earle (2008) and Vigotsky, Harper, Ryan, and Contreras (2015) by performing as many repetitions with what each subject perceived to be a moderately heavy load. Order of the testing was randomized.

Subjects were asked to wear appropriate clothing for access to the EMG electrode placement sites. Before placing the electrodes on the skin, excess hair was removed with a razor, and skin was cleaned and abraded using an alcohol swab. After preparation, self-adhesive disposable silver/silver chloride pre-gelled dual snap surface bipolar electrodes (Noraxon Product #272, Noraxon USA Inc, Scottsdale, AZ) with a diameter of 1 cm and an inter-electrode distance of 2 cm were attached in parallel to the fibers of the right upper gluteus maximus, lower gluteus maximus, biceps femoris, and vastus lateralis in concordance with the recommendations of Hermens et al. (1999) and Fujisawa et al. (2014). More specifically, "[upper gluteus maximus] electrodes were placed two finger's width above the line just under the spina iliaca posterior superior and the trochanter major; [lower gluteus maximus] electrodes were set below the same line" (Fujisawa et al., 2014), biceps femoris electrodes were "placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia" (Hermens et al., 1999), and vastus lateralis electrodes were "placed at 2/3 on the line from the anterior spina iliaca superior to the lateral side of the patella" (Hermens et al., 1999). After the electrodes were secured, a quality check was performed to ensure EMG signal validity.

Ten minutes after estimated 10 RM testing, maximum voluntary isometric contraction (MVIC) testing was performed. For the gluteus maximus, two MVIC positions were tested. The first involved a prone bent-leg hip extension against manual resistance applied to the distal thigh, as utilized by Boren and colleagues (Boren et al., 2011), and the second involved a standing glute squeeze. Pilot data from our lab

revealed that some subjects achieve higher levels of gluteus maximus EMG amplitude with the standing glute squeeze than during the prone bent-leg hip extension against manual resistance. Both conditions were recorded and EMG was normalized to whichever contraction elicited greater EMG amplitude. Biceps femoris MVIC was determined by having the subject lay prone and produce maximum knee flexion torque at 45° knee flexion against manual resistance applied to the distal leg just above the ankle, as reported by Mohamed and colleagues (Mohamed, Perry, & Hislop, 2002). Two vastus lateralis MVIC positions were used. The first had the subject sit and produce maximum knee extension torque against manual resistance applied to the distal leg just above the ankle at 90° hip flexion and 90° knee flexion, as detailed by Kong and Van Haselen (2010) (except without the use of an isokinetic dynamometer), while the second used a 90° hip flexion and 180° knee position. Whichever contraction elicited greater EMG amplitude was used for normalization. In all MVIC positions, subjects were instructed to contract the tested muscle “as hard as possible”.

After 10 minutes of rest following MVIC testing, subjects performed ten repetitions utilizing their estimated 10 RM of front, full, and parallel squats in a randomized order and counterbalanced fashion. During all squat variations, subjects’ feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. For the front squat, the barbell was placed across the anterior deltoids and clavicles. Subjects fully flexed their elbows to position the upper arms parallel to the floor (Figure 5.1) (Gullett et al., 2009). During both back squat variations (full and parallel), the barbell was placed in the high bar position across the shoulders on the trapezius, slightly above the posterior aspect of the deltoids (Figure 5.2, Figure 5.3) (Gullett et al., 2009). In both the front and full squat, subjects descended until the knees were maximally flexed (Figure 5.1, Figure 5.2) (Robertson et al., 2008). Descent during the parallel squat was limited to the point at which the tops of the thighs were parallel

with the floor (Figure 5.3) (Pierce, 1997). Subjects were given five minutes of rest between sets. No pre-determined tempo was set as to better mimic typical training conditions.



Figure 5.1. Front squat form.



Figure 5.2. Full squat form.



Figure 5.3. Parallel squat form.

Raw EMG signals were collected at 2000 Hz with a gain of 500 by a Myotrace 400 EMG unit (Noraxon USA Inc, Scottsdale, AZ). Data was sent in real time to a computer via Bluetooth and recorded and analyzed by MyoResearch 3.6 Clinical Applications software (Noraxon USA Inc., Scottsdale, AZ). A 10-500 Hz bandpass filter was applied to EMG data. Signals of all 10 repetitions were rectified and smoothed with a root mean square (RMS) algorithm with a 100 ms window. Mean and peak data were normalized to a mean peak of a 1000 ms window from the MVIC trials.

While peak values allow for all near-instantaneous increases in muscle activation to be seen, the mean is robust to both movement artifact and time, thus providing a reliable average of EMG amplitude over the entire movement (Renshaw et al., 2010).

Repeated measures analyses of variance (ANOVA) were performed using Stata 13 (StataCorp LP, College Town, TX), wherein mean and peak EMG between exercises, within subjects, and within muscle effects were calculated. Bonferroni *post hoc* tests were performed on any measure that achieved a main effect. Alpha was set to 0.05 for significance. Partial η^2 effect sizes were calculated and reported, as were their 95% confidence intervals (95% CI). Partial η^2 effect sizes were interpreted based upon the guidelines of Cohen (1988); that is, a partial η^2 of 0.02 is small, 0.13 is medium, and 0.26 is large.

5.3 Results

No statistically significant differences ($p \leq 0.05$) were found between any measured outcomes except for vastus lateralis peak EMG, which revealed no pairwise differences.

No main effects were found for mean EMG amplitude of the upper gluteus maximus ($p = 0.98$; $F_{2,24} = 0.02$; partial $\eta^2 = 0.00$; 95% CI = 0.0 – 1.0), lower gluteus maximus ($p = 0.474$; $F_{2,24} = 0.77$; partial $\eta^2 = 0.06$; 95% CI = 0.0 – 0.24), biceps femoris ($p = 0.31$; $F_{2,24} = 1.23$; partial $\eta^2 = 0.09$; 95% CI = 0.0 – 0.29), and vastus lateralis ($p = 0.21$; $F_{2,24} = 1.69$; partial $\eta^2 = 0.12$; 95% CI = 0.0 – 0.33) (Table 5.1). The partial η^2 values suggest small effects were observed for the upper gluteus maximus, lower gluteus maximus, and biceps femoris, and a medium effect for the vastus lateralis. However, it cannot be said that these effects were not due to chance alone.

No main effects were found for peak EMG amplitude for the upper gluteus maximus ($p = 0.90$; $F_{2,24} = 0.10$; partial $\eta^2 = 0.01$; 95% CI = 0.0 – 0.10), lower gluteus maximus ($p = 0.60$; $F_{2,24} = 0.52$; partial $\eta^2 = 0.04$; 95% CI = 0.0 – 0.21), or biceps

femoris ($p = 0.96$; $F_{2,24} = 0.04$; partial $\eta^2 = 0.00$; 95% CI = 0.0 – 0.04). Although a main effect was found for peak vastus lateralis EMG activity ($p = 0.03$; $F_{2,24} = 4.27$; partial $\eta^2 = 0.26$; 95% CI = 0.0 – 0.47), Bonferroni *post hoc* testing revealed no pairwise effects (Table 5.1). The partial η^2 values suggest small effects were observed for the lower gluteus maximus and biceps femoris, and a large effect for the vastus lateralis; however, for the lower gluteus maximus and biceps femoris, it cannot be said that these effects were not due to chance alone.

Table 5.1. Mean \pm SD of EMG (%MVIC) values in the parallel, full, and front squat.

		Parallel	Full	Front
Mean	Upper gluteus maximus	29.4 \pm 16.5	29.6 \pm 16.3	29.2 \pm 14.4
	Lower gluteus maximus	45.3 \pm 23.5	42.2 \pm 21.5	43.9 \pm 20.8
	Biceps femoris	14.9 \pm 6.6	14.4 \pm 6.41	13.1 \pm 4.70
	Vastus lateralis	110 \pm 47.2	124 \pm 67.4	124 \pm 73.0
Peak	Upper gluteus maximus	84.9 \pm 42.9	88.1 \pm 47.8	84.6 \pm 50.5
	Lower gluteus maximus	130 \pm 60.5	125 \pm 55.4	135 \pm 55.7
	Biceps femoris	37.5 \pm 18.4	38.6 \pm 16.8	39.4 \pm 22.8
	Vastus lateralis	244 \pm 122	281 \pm 166	303 \pm 192

5.4 Discussion

Our hypothesis was partially confirmed in that there were no observable differences between full, front, and parallel squats in the UGM, LGM, and biceps femoris. However, the front and full squat failed to elicit significantly greater vastus lateralis EMG amplitude than the parallel squat. Unsurprisingly, subjects utilized the greatest amount of load in the parallel squat (53.1 \pm 17.0 kg), followed by full (46.7 \pm 17.1 kg) and front (39.2 \pm 15.6 kg) squats, respectively. These findings are in line with Gullett et al. (2009), Gorsuch et al. (2013), and Yavuz et al. (2015), where investigators found no significant differences between mean EMG amplitude of the muscles measured in this

study. Specifically, Gullett et al. (2009) found no differences ($p \leq 0.05$) in vastus lateralis or biceps femoris EMG during front and parallel squats, Gorsuch et al. (2013) did not find significant differences in biceps femoris EMG during partial and parallel squats, and Yavuz et al. (2015) did not find statistical differences in gluteus maximus, biceps femoris, or vastus lateralis EMG during front and back squats. However, Gullett et al. (2009) also investigated the rectus femoris, vastus medialis, semitendinosus, and erector spinae, Gorsuch et al. (2013) the rectus femoris, erector spinae, and gastrocnemius, and Yavuz et al. (2015) the vastus medialis, rectus femoris, semitendinosus, and erector spinae. Thus, it is possible that had this study investigated these muscles, too, differences may have been observed. It should be noted that our results differ from Caterisano et al. (2002), who found that gluteus maximus EMG amplitude significantly increased with depth. However, as noted by Clark et al. (2012), Caterisano et al. (2002) did not utilize relative loading, which seems to have affected the outcome, as in this study, subjects used 12.8% greater 10RM loads during the parallel squat compared to during the full squat.

Although no significant pairwise differences were observed between any measured outcomes, peak vastus lateralis EMG activity during front squats was about 21.5% greater than during parallel squats despite lighter 10 RM loads. This large difference in EMG amplitude combined with the large effect size occurring without a significant effect suggests that our study may have been underpowered. Additionally, visual inspection of the results reveals a non-significant trend for increasing peak vastus lateralis EMG amplitude from the parallel squat to the full squat to the front squat, and for increasing mean vastus lateralis EMG amplitude from the parallel squat to the full and front squat, in which a medium effect size was observed (Table 5.1). These findings seem to be congruent with those of Bryanton et al. (2012), who reported that the net knee extension moment increased to a greater extent with increasing squat depth than

with increasing squat load. The findings may also relate to the more favorable training adaptations observed by Bloomquist et al. (2013), where investigators found that squats using a greater range of motion led to greater quadriceps hypertrophy. It is unfortunate that Bloomquist et al. (2013) did not measure gluteus maximus hypertrophy, nor has it been measured in any other barbell squat study to the authors' knowledge.

As expected, biceps femoris was not highly activated during any of the squat variations. This is in concordance with other studies (Aspe & Swinton, 2014; Gullett et al., 2009; Wretenberg et al., 1996), including Ebben et al. (2000), who concluded that squatting was insufficient for hamstring development. On the basis of these findings, it seems logical that other exercises, such as leg curls and stiff leg deadlifts, should be implemented to ensure maximal hamstring development.

Maximum hip and knee moments in the squat occur in considerable hip and knee flexion (Cotter et al., 2013; Escamilla, Fleisig, Lowry, et al., 2001; Wretenberg et al., 1996). Because the greatest EMG amplitude is elicited from the gluteus maximus in full hip extension (Worrell et al., 2001) and from the biceps femoris in full hip extension and 45° knee flexion (Mohamed et al., 2002), this may explain why the squat does not maximally activate these muscles. Alternatively, the hamstrings might not be highly activated because increasing hamstrings reliance necessitates greater knee extensor moments to counter the hamstrings' knee flexion moment (Bryanton et al., 2015). However, the MVIC position for the vastus lateralis is obtained with both the hip and knee flexed to 90° (Kong & Van Haselen, 2010). This is the knee angle at which, in the squat, there is a notable amount of net knee extension moment (Escamilla, Fleisig, Lowry, et al., 2001). This may therefore explain the higher EMG values from the vastus lateralis than the gluteus maximus or biceps femoris. The seemingly high vastus lateralis values in this investigation may also be due to the sample being female subjects, whereas most previous studies utilized male subjects. Research has shown that

women adopt more knee-dominant movement patterns, which would necessarily require more torque from and therefore more activation of the quadriceps (Lynn & Noffal, 2012). Alternatively, it could be due to decreased stability while performing the MVIC trial, as subjects were not strapped into a dynamometer – the subjects sat on a flat bench and the investigator held the leg stable while simultaneously generating manual resistance against the lower limb.

The front squat is performed with the torso more upright, while the back squat is performed with more forward lean (Diggin et al., 2011). Despite this difference, hip extension torque has been found to be similar in males (Russell & Phillips, 1989), which may explain why there were no significant differences in gluteus maximus or biceps femoris EMG between front and back squats in this study. However, further research must be completed in females to confirm this theorization. It should be noted that due to individual differences (Elson & Aspinall, 2008) and pathologies such as femoroacetabular impingement (Lamontagne, Kennedy, & Beaulé, 2009), the deep squat may not be a viable option for all individuals. More specifically, Elson and Aspinall (2008) described a large variability of hip flexion mobility between human subjects (80-140°), whereby after each subject reached his or her hip flexion limit, posterior pelvic tilt occurred.

A limitation of investigating the deep squat is the inability to standardize depth amongst subjects. Inter-individual variances in lower body mass, flexibility, and other factors ultimately determine how low a given subject can squat without compromising exercise technique. The authors did not measure the specific joint angles in the full squat, but rather, instructed subjects to descend as low as possible while maintaining proper form. Whether such differences has an impact on lower body muscle activation remains to be elucidated.

This was the first study to compare front, parallel, and full squats in women. However, generalizability is specific to young, resistance-trained women. Considering that highly trained women have been shown to possess greater hip mobility compared to men (Drezewska, Galuszka, & Sliwinski, 2012) and that many men prefer the low bar squat position as opposed to the high bar squat position we used in this study, it is recommended that more research be performed to gain further insight as to how these squat variations in addition to low bar squat variations affect the EMG amplitude in men and other populations.

The front squat appears to be a viable alternative to the back squat since muscle activation is similar between the two variations. Given that both long term training and acute biomechanical investigations favor deep squats over parallel or partial squats, it is recommended that an athlete squat as deeply as he or she can, provided he or she can do so safely. However, deep squats are not appropriate for everyone, as it is necessary to have the requisite hip and ankle mobility to safely and properly descend into a deep squat. Individuals with limited hip flexion ability, whether due to pathologic or morphologic variance, will not be able to squat as deeply while maintaining a lordotic curvature of the spine, which could lead to back injury over time.

***A COMPARISON OF GLUTEUS MAXIMUS, BICEPS FEMORIS,
AND VASTUS LATERALIS EMG ACTIVITY IN THE BARBELL,
BANDED, AND AMERICAN HIP THRUST VARIATIONS***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**Journal of Applied Biomechanics
In Press**

(Appendix 3f)

6.0 Prelude

In Chapter 2, it was discovered that no EMG research currently exists examining the barbell hip thrust exercise. In Chapter 3, it was found that horizontally loaded hip extension exercises have very high moment requisites at end-range hip extension, or the exercise's lockout. In Chapter 4, it was determined that end-range hip extension is where the gluteus maximus elicited its highest level of activation. Since the hip thrust exercise is a horizontally-loaded hip extension exercise, it is likely to require large torques from the hip extensors in order to lock out the load and achieve full hip extension. It is also likely to require high levels of activation from the gluteus maximus at this end-range position.

There are several popular forms of the hip thrust – namely, the barbell, American, and band hip thrusts. In Chapter 5, three different squat variations were tested in order to determine the differences and similarities in muscle activation so that the ideal variation can be used in Chapter 10. Similar research needs to be undertaken for the hip thrust pattern, and therefore, this chapter will seek to compare the hip and thigh activity between the three aforementioned hip thrust variations, which will inform the training studies included later in this thesis.

6.1 Introduction

Bridging exercise variations are commonly employed for both rehabilitation (Czaprowski et al., 2014; Reiman, Bolgla, & Loudon, 2012; Vangelder, Hoogenboom, & Vaughn, 2013) and enhancement of sports performance (Crow, Buttifant, Kearny, & Hrysomallis, 2012; DiStefano et al., 2010; Healy & Harrison, 2014). For such purposes, both bodyweight and loaded bridging exercise variations are performed. Consequently, bodyweight bridging exercises have frequently been compared to one another in the

literature. For example, unilateral bridges have been shown to elicit approximately double the upper gluteus maximus electromyography (EMG) activity than do bilateral bodyweight bridges (Selkowitz, Beneck, & Powers, 2013). However, despite their popularity for strength and conditioning, no loaded bridges have been compared. Barbell exercises are a staple in strength and conditioning programs around the world and typically outperform machine exercises in muscle activation (McCaw & Friday, 1994; Schwanbeck et al., 2009). The barbell hip thrust, introduced in the literature by Contreras et al. (2011) is a loaded bridging exercise used to target the hip extensor musculature against barbell resistance. It has recently been suggested that the barbell hip thrust can enhance speed, horizontal force production, and gluteus maximus hypertrophy (Beardsley & Contreras, 2014; Contreras et al., 2011; de Lacey, Brughelli, McGuigan, & Hansen, 2014; Eckert & Snarr, 2014). Moreover, recent work from our lab found that the barbell hip thrust elicited superior gluteus maximus and biceps femoris EMG activity in comparison to the barbell back squat (Contreras, Vigotsky, Schoenfeld, Beardsley, & Cronin, 2015a). This may be because the barbell allows the lifter to maintain more consistent tension on the hip extensors throughout the entire range of motion.

In sports science research, exercises are commonly compared to one another to help determine which exercise leads to more favorable changes in variables of interest. For example, muscle activation is often compared between exercises (Aspe & Swinton, 2014; Comfort, Allen, & Graham-Smith, 2011b; Ebben et al., 2009; Escamilla, Fleisig, Lowry, et al., 2001; Escamilla et al., 2000; Escamilla et al., 2002; Gullett et al., 2009; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; Swinton, Stewart, Agouris, Keogh, & Lloyd, 2011; Swinton, Stewart, Lloyd, Agouris, & Keogh, 2012). To the authors' knowledge, no study to date has examined bridging variations that utilize external resistance, nor has any study to date compared one variation versus another.

The American hip thrust is similar to the barbell hip thrust but involves posterior pelvic tilt (PPT), which mimics hip extension (Neumann, 2010). Research has shown that PPT can enhance gluteus maximus activation (Oh et al., 2007; Queiroz et al., 2010), as our group has previously shown in the plank (Schoenfeld, Contreras, Tiriyaki-Sonmez, Willardson, & Fontana, 2014). It is therefore plausible that combining PPT with hip extension during the hip thrust will promote greater gluteus maximus activation. However, performing PPT during the hip thrust seems to involve a greater degree of neuromuscular coordination, which some lifters have trouble mastering.

Bands have recently been shown to elicit similar levels of EMG activation compared to free weights (Saeterbakken, Andersen, Kolnes, & Fimland, 2014; Sundstrup et al., 2012) and to alter the torque-angle curve to produce more tension at shorter muscle lengths (McMaster, Cronin, & McGuigan, 2009; McMaster, Cronin, & McGuigan, 2010). Because the gluteus maximus elicits the greatest amount of EMG activity at end-range hip extension (Worrell et al., 2001), it is plausible that the band hip thrust might outperform the barbell in peak gluteus maximus EMG. However, since bands fail to maintain consistent levels of tension throughout the movement, some of the exercise range of motion is lacking adequate resistance.

The purpose of this investigation was to compare the EMG activity of the upper gluteus maximus (UGM), lower gluteus maximus (LGM), biceps femoris (BF), and vastus lateralis (VL) during the barbell, band, and American hip thrust variations. It was hypothesized that barbell hip thrust would elicit greater UGM, LGM, BF, and VL EMG activity than the band and American hip thrusts would.

6.2 Methods

A convenience sample of thirteen healthy women participated in this study. Subjects (age = 28.9 ± 5.1 years; height = 164.3 ± 6.3 cm; body mass = 58.2 ± 6.4 kg) had 7.0 ± 5.8 years of resistance training experience and had a 10 RM of 87.4 kg in the barbell hip thrust. Inclusion criteria required subjects to be between 20 to 40 years of age, have at least three years of consistent resistance training experience, and be familiar with performance of the hip thrust exercise. All subjects were healthy and denied the existence of any current musculoskeletal or neuromuscular injuries, pain, or illnesses. Subjects filled out an Informed Consent and Physical Activity Readiness Questionnaire (PAR-Q). Any subject that answered “yes” to any of the questions on the PAR-Q was excluded from the study. Subjects were advised to refrain from training their lower body for 72 hours prior to testing. To ensure acceptable performance in the barbell hip thrust, subjects performed each movement using only a barbell while the lead researcher evaluated technique. If a subject reported pain, discomfort, or failed to perform the movement correctly, she was excluded from participation. If, for any reason, a subject could not complete a trial, her data was discarded. The study was approved by the Auckland University of Technology Ethics Committee.

Subjects first performed a 10-minute general warm-up consisting of various dynamic stretches for the lower body musculature. Afterwards, three progressively heavier specific warm-up sets were performed for the hip thrust exercise. Next, subjects' 10 RM in barbell, band, and American hip thrusts were calculated using the methods described by Baechle and Earle (2008), by performing as many repetitions with what each subject perceived to be a moderately heavy load. Order of the testing was randomized.

Subjects were asked to wear appropriate clothing for access to the EMG electrode placement sites. Before placing the electrodes on the skin, excess hair was removed with a razor, and skin was cleaned and abraded using an alcohol swab. After preparation, self-adhesive disposable silver/silver chloride pre-gelled dual snap surface bipolar electrodes (Noraxon Product #272, Noraxon USA Inc., Scottsdale, AZ) with a diameter of 1 cm and an inter-electrode distance of 2 cm were attached in parallel to the fibers of the right UGM, LGM, BF, and VL in concordance with the recommendations of Hermens et al. (1999) and Lyons et al. (1983). After the electrodes were secured, a quality check was performed to ensure EMG signal validity.

Ten minutes after 10 RM testing, maximum voluntary isometric contraction (MVIC) testing was performed. For the gluteus maximus, two MVIC positions were tested. The first involved a prone bent-leg hip extension against manual resistance applied to the distal thigh as utilized by Boren et al. (2011), and the second involved a standing glute squeeze. Pilot data from our lab revealed that a minority of subjects achieved higher levels of gluteus maximus EMG activity with the standing glute squeeze than during the prone bent-leg hip extension against manual resistance. Thus, both conditions were recorded and EMG was normalized to whichever contraction elicited greater EMG activity. BF MVIC was determined by having the subject lie prone and produce maximum knee flexion torque at 45° knee flexion against manual resistance applied to the distal leg just above the ankle, as found to be superior by Mohamed et al. (2002). Two VL MVIC positions were used. The first had the subject sit and produce maximum knee extension torque against manual resistance applied to the distal leg just above the ankle at 90° hip flexion and 90° knee flexion, as found to be superior by Kong and Van Haselen (2010), while the second used a 90° hip flexion and 180° knee position. Whichever contraction elicited greater EMG activity was used for

normalization. In all MVIC positions, subjects were instructed to contract the tested muscle “as hard as possible”.

After 10 minutes of rest following MVIC testing, subjects performed 10 repetitions utilizing their estimated 10 RM of the barbell, band, and American hip thrusts in a counterbalanced, randomized order. In accordance with Contreras et al. (2011), the barbell hip thrust was performed with the subjects’ backs on a bench approximately 16 in high. The subjects’ feet were slightly wider than shoulder width apart with toes pointed forward or slightly outward. The barbell was padded with a thick bar pad and placed over the subjects’ hips. The subjects were instructed to thrust the bar upwards while maintaining a neutral spine and pelvis (Figure 6.1). A full range of motion was used for each repetition, beginning with the bar touching the ground and ending in full hip extension. The American hip thrust was performed in a similar fashion but the subjects were positioned on the bench such that the inferior angle of the scapulae rested on the bench. Subjects combined hip extension and posterior pelvic tilt in this variation, which required a blend of anterior pelvic tilt and hip flexion during the eccentric portion of the movement and posterior pelvic tilt and hip extension during the concentric portion of the movement (Figure 6.2). The band hip thrust was performed identically to the barbell hip thrust but with elastic resistance bands instead of a barbell (Figure 6.3). In each variation, hip range of motion was kept consistent, which required that subjects reverse the movement in mid-air with the American hip thrust, since the bar does not touch the ground during this variation. Subjects were given five minutes of rest between sets. No pre-determined tempo was set so as to better represent true training conditions.



Figure 6.1. Barbell hip thrust form.

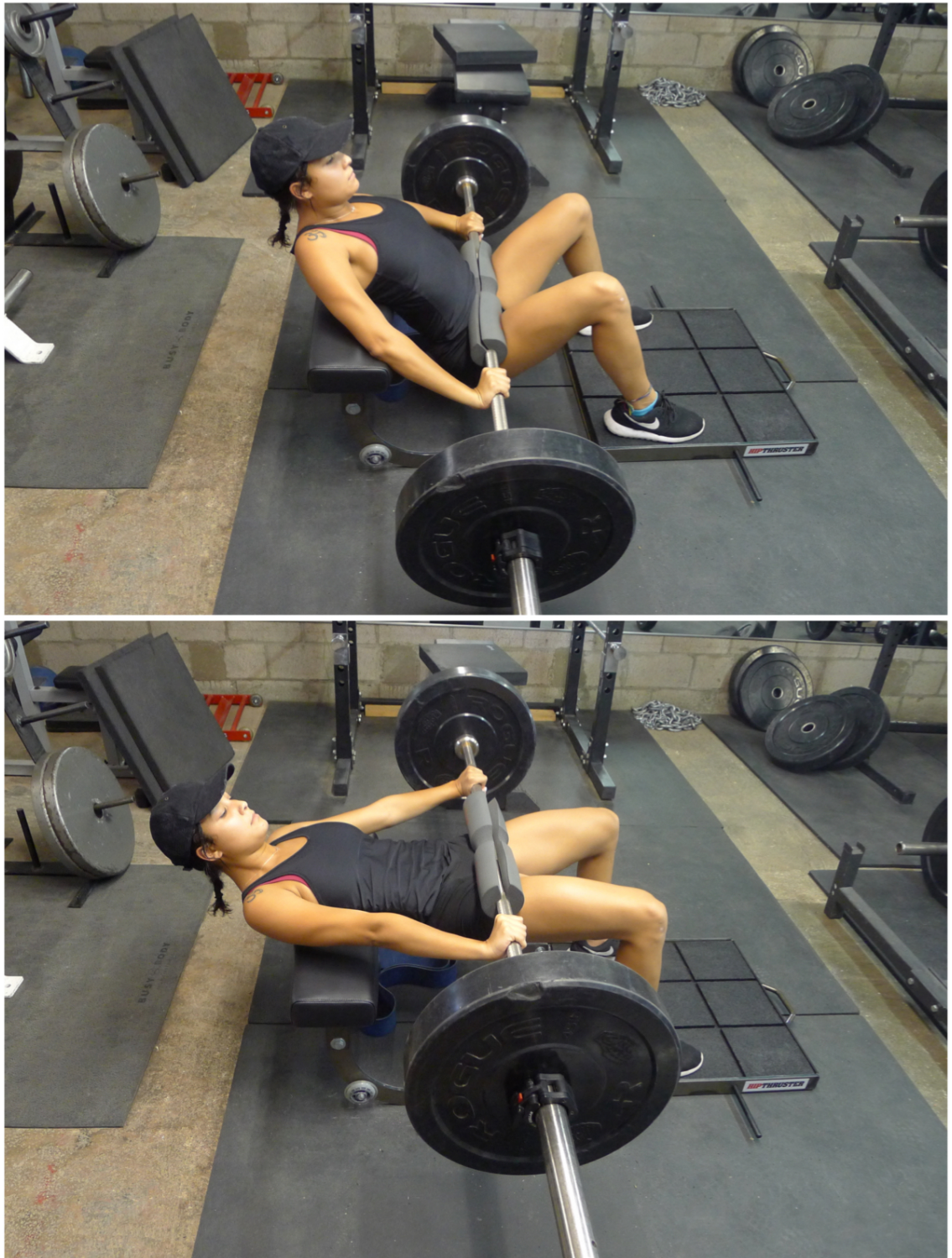


Figure 6.2. American hip thrust form.

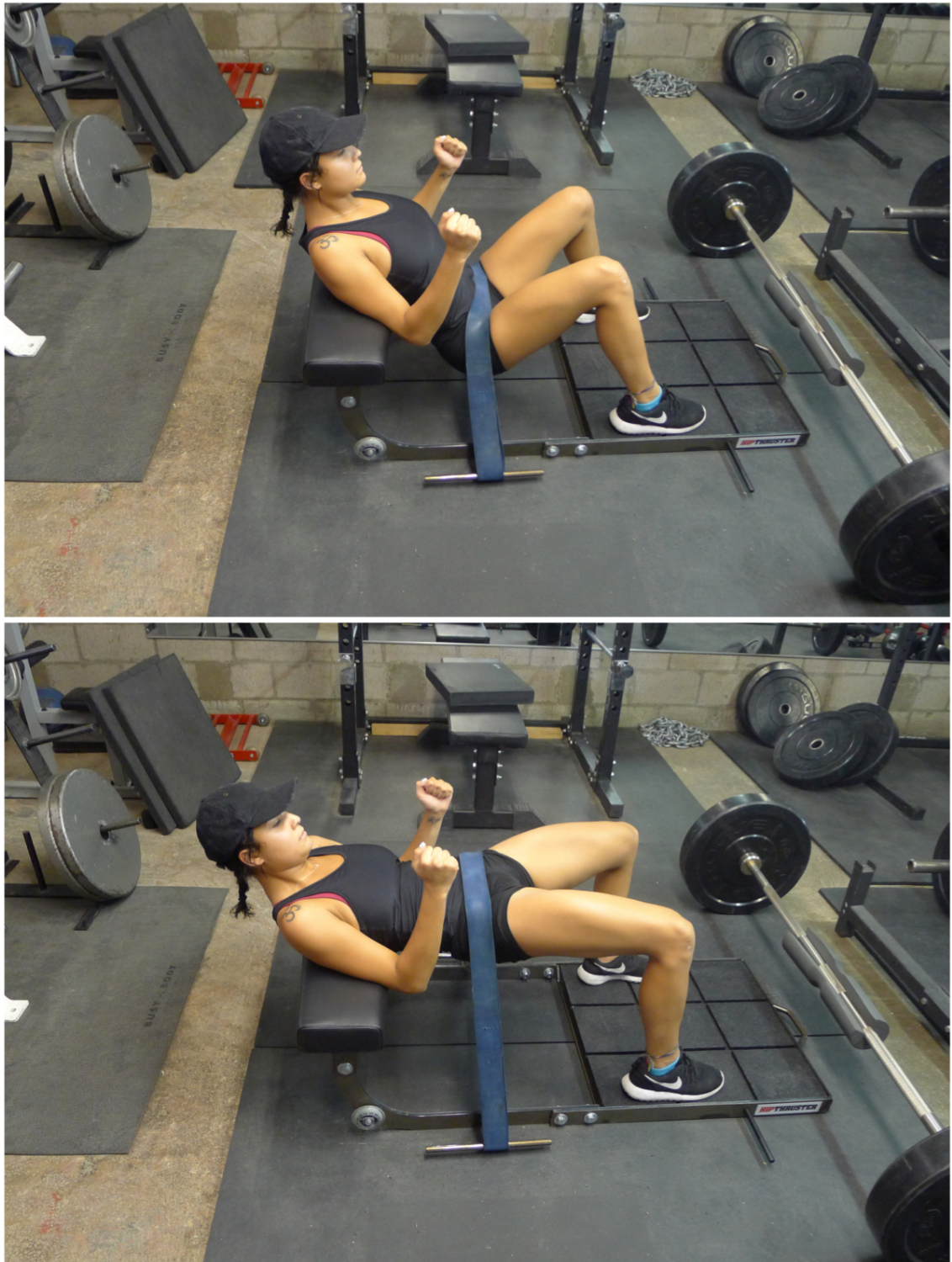


Figure 6.3. Band hip thrust form.

Raw EMG signals were collected at 2000 Hz by a Myotrace 400 EMG unit (Noraxon USA Inc, Scottsdale, AZ). Data was sent in real time to a computer via Bluetooth and recorded and analyzed by MyoResearch 3.6 Clinical Applications

software (Noraxon USA Inc., Scottsdale, AZ). Signals of all 10 repetitions for the dynamic sets and for all three seconds of the isoholds were rectified and smoothed with a root mean square (RMS) algorithm with a 100 ms window. Mean and peak data were normalized to a mean peak of a 1000 ms window from the MVIC trials.

One-way analyses of variance (ANOVA) with repeated measures were performed using Stata 13 (StataCorp LP, College Town, TX). Bonferroni's *post hoc* tests were performed on any measure that achieved a main effect. Alpha was set to 0.05 for significance. Partial η^2 effect sizes were calculated and reported, as were their 95% confidence intervals (95% CI).

6.3 Results

A main effect was observed for mean UGM ($p < 0.001$; $F_{2,24} = 9.60$; partial $\eta^2 = 0.44$; 95% CI = 0.11–0.62), but Tukey's *post hoc* testing revealed no pairwise effects. No main effects were observed for mean LGM ($p = 0.49$; $F_{2,24} = 0.74$; partial $\eta^2 = 0.06$; 95% CI = 0–0.24), BF ($p = 0.48$; $F_{2,24} = 0.76$; partial $\eta^2 = 0.06$; 95% CI = 0–0.24), or VL ($p = 0.56$; $F_{2,24} = 0.59$; partial $\eta^2 = 0.05$; 95% CI = 0–0.22) EMG activity (Table 6.1).

A main effect was noted for peak UGM ($p = 0.03$; $F_{2,24} = 4.03$; partial $\eta^2 = 0.25$; 95% CI = 0–0.46), but Tukey's *post hoc* testing revealed no pairwise effects. No main effects were observed for peak LGM ($p = 0.43$; $F_{2,24} = 0.87$; partial $\eta^2 = 0.07$; 95% CI = 0–0.26), BF ($p = 0.56$; $F_{2,24} = 0.58$; partial $\eta^2 = 0.05$; 95% CI = 0–0.22), or VL ($p = 0.26$; $F_{2,24} = 1.41$; partial $\eta^2 = 0.11$; 95% CI = 0–0.31) EMG activity (Table 6.1).

In addition to statistical comparisons, the number of subjects to achieve maximum EMG amplitude in each position was summed and compared in Table 6.2.

Table 6.1. Mean \pm SD of EMG (%MVIC) values for the barbell, band, and American hip thrusts.

		Barbell	Band	American
Mean	Upper gluteus maximus	69.5 \pm 32.6	49.2 \pm 26.5	57.4 \pm 34.8
	Lower gluteus maximus	86.7 \pm 27.0	79.2 \pm 29.9	89.9 \pm 32.4
	Biceps femoris	40.8 \pm 22.1	36.8 \pm 18.0	44.2 \pm 20.0
	Vastus lateralis	99.5 \pm 92.3	93.5 \pm 70.9	87.3 \pm 65.0
Peak	Upper gluteus maximus	172 \pm 91.0	120 \pm 73.8	157 \pm 126
	Lower gluteus maximus	216 \pm 83.8	185 \pm 94.4	200 \pm 71.1
	Biceps femoris	86.9 \pm 38.8	89.4 \pm 40.4	98.7 \pm 44.9
	Vastus lateralis	216 \pm 194	185 \pm 139	177 \pm 128

Table 6.2. Number of subjects (% of subjects) to achieve maximal activation in each exercise.

		Barbell	Band	American
Mean	Upper gluteus maximus	11 (84.6)	1 (7.70)	1 (7.70)
	Lower gluteus maximus	6 (46.2)	2 (15.4)	5 (38.5)
	Biceps femoris	3 (23.1)	1 (7.70)	9 (69.2)
	Vastus lateralis	6.5 (50.0)	3 (23.1)	3.5 (26.9)
Peak	Upper gluteus maximus	10 (76.9)	2 (15.4)	1 (7.70)
	Lower gluteus maximus	5 (38.5)	4 (30.8)	4 (30.8)
	Biceps femoris	3 (23.1)	5 (38.5)	5 (38.5)
	Vastus lateralis	6.5 (50.0)	2 (15.4)	4.5 (34.6)

“Tied” values were “split”; e.g., if one subject achieved the same value in the barbell and band hip thrusts, 0.5 were added to each.

6.4 Discussion

Contrary to the authors’ hypotheses, no differences were observed in mean or peak EMG activity of the UGM, LGM, BF, and VL between any of the hip thrust variations

despite the American hip thrust (91.9 ± 18.5 kg) utilizing slightly more load than the barbell hip thrust (87.4 ± 19.3 kg). This may be because of the positioning in the American hip thrust, in that the lever arm from the bench to the hips is shorter, thus resulting in a smaller moment arm, so a larger load would be needed to yield similar torque requirements.

Nevertheless, as expected, the barbell, band, and American hip thrust conditions all displayed very high levels of mean EMG activity in the UGM ($69.5 \pm 32.6\%$, $49.2 \pm 26.5\%$, and $57.4 \pm 34.8\%$, respectively) and LGM ($86.7 \pm 27.0\%$, $79.2 \pm 29.9\%$, and $89.9 \pm 32.4\%$, respectively). These results show that all three exercises display greater EMG activity in the LGM than the suggested threshold of 60% of MVIC for the development of muscular strength and size and that the barbell hip thrust also displays greater EMG activity in the UGM (Andersen et al., 2006; Kraemer et al., 2002). This confirms the use of the loaded hip thrusts for gluteus maximus development. Additionally, these findings demonstrate the mean EMG amplitude elicited by loaded hip thrusts for the gluteus maximus is markedly greater than what has been reported in an unloaded bridge (Jang, Kim, & Oh, 2013). This is to be expected, as other unloaded exercises have failed to elicit similar amplitudes compared to their loaded counterpart. For example, Paoli, Marcolin, and Petrone (2009) noted a 31% difference between VL EMG in bodyweight and 70% 1 RM squats. In a wider context, this seems to be because intensity of load is a key driver of muscle activation, as a recent study demonstrated in the leg press exercise (Schoenfeld, Contreras, Willardson, Fontana, & Tiriyaki-Sonmez, 2014), and one view of unloaded exercises is that they are simply loaded exercises involving very low intensity of load.

Although EMG activity was similar between variations, barbell hip thrust offers potential advantages over the band and American hip thrusts. Owing to strength curve alterations in elastic implements (McMaster et al., 2009; McMaster et al., 2010), the

barbell hip thrust provides more consistent levels of tension throughout the movement compared to the band hip thrust. Moreover, the barbell hip thrust has a more graded learning curve than the American hip thrust, as one does not have to learn pelvic control (PPT) in order to perform the barbell hip thrust. While there were large inter-individual variations in terms of which exercise elicited the greatest EMG activity in each muscle (Table 6.2), it is worth noting that 11 and 10 out of the 13 subjects exhibited the greatest mean and peak upper gluteus maximus EMG activity, respectively, during performance of the barbell hip thrust.

A key limitation of our study was that because bands were used for the band hip thrust, estimating subjects' 10 RM was not possible using the methods described by Baechle and Earle (2008). In the band hip thrust, the loads were estimated by equating loads used during the barbell hip thrust with peak forces elicited during unpublished pilot data collection using a force plate, and slight adjustments were made based on feedback from the subjects. That is, loads used during the band hip thrust elicited similar peak ground reaction forces to those used during the barbell hip thrust. Thus, the 10 RM utilized in the band hip thrust may not be equivalent in terms of intensity of load to that during the barbell and American hip thrust conditions. Since the EMG outcomes were similar and, subjectively, subjects tended to fatigue in a similar manner during the band hip thrust trials, it is presumed that bands used were approximately, albeit not exactly, 10 RM. Nevertheless, if exact 10 RM loads were used in comparing the barbell, band, and American hip thrust conditions, it is conceivable that different results might have been obtained.

Another limitation of this study was that it was performed only in young, resistance-trained female subjects. Thus, a very homogenous sample was used and caution is required in extrapolating these results to other populations, including

untrained individuals, males, and the elderly. Therefore, it seems advisable that this experiment should be replicated in different populations.

Finally, this study was limited in that the kinematic differences between the three loaded hip thrust variations were not explored. By observation, it seems that barbell and band hip thrusts involve a greater range of movement than does the American hip thrust exercise variation. Additionally, it may be the case that both EMG activities of the gluteus maximus and BF and of the hip extension torque vary differently with changing hip angle between the three exercise variations, but since no measurement was taken of these variables with changing hip angle, this remains unclear. Moreover, this study only considered the effect of 10 RM and different loads and set and repetition schemes should be examined. Finally, given emerging evidence that combining free weight exercise with resistance bands enhances strength in the bench press and back squat (Anderson et al., 2008; Bellar et al., 2011), it is conceivable that similar benefits could be achieved from a combined approach in the hip thrust. This hypothesis also warrants further investigation.

Since similar EMG activity was observed in the barbell, band, and American hip thrusts, exercise selection should be made based on other factors. Individuals with extension-induced low back pain may prefer the American hip thrust, as it involves PPT, which reduces the risk of lumbar hyperextension and therefore hyperextension-induced pathology, such as spondylolysis (Dunn, Proctor, & Day, 2006). For some, band hip thrusts may be preferable to either the American hip thrust or the barbell hip thrust, as bands can be more comfortable on the hips, are more convenient due to their portable nature, or are more motivating as they appear to be effective because they feel the gluteus maximus working more than with the barbell hip thrust.

Nevertheless, for developing the gluteus maximus, the barbell hip thrust would seem to be the best single option for a majority of lifters. It seems to provide the most

constant tension throughout the whole range of motion, requires little motor learning with regards to pelvic control (as is the case with American hip thrust), has been found to involve the greatest mean EMG activity in the UGM and LGM in 11 out of 13 subjects in this study, and involves mean EMG activity above the recommended threshold of 60% of MVIC for both the UGM and LGM, while the American hip thrust and band hip thrust only achieves >60% in UGM.

***A COMPARISON OF GLUTEUS MAXIMUS, BICEPS FEMORIS,
AND VASTUS LATERALIS EMG ACTIVITY IN THE BACK SQUAT
AND BARBELL HIP THRUST EXERCISES***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**Journal of Applied Biomechanics
31(6), 452-458**

(Appendix 3g)

7.0 Prelude

It was found in Chapters 5 and 6 that similar levels of hip and thigh muscle activity were achieved between squat and hip thrust variations. However, these two exercises have not yet been compared to each other. If the hip thrust is shown to achieve higher levels of hip extensor activation than the squat, then it is possible that it is better suited to improve actions that rely heavily upon the hip extensors, including sprint acceleration and horizontal pushing. This chapter will seek to explore the differences in hip and thigh muscle activation between the squat and hip thrust.

7.1 Introduction

The gluteus maximus is considered to be important for both sports performance and injury prevention due to its multiplanar contribution to high-speed locomotion and knee stabilization (Dorn et al., 2012; Roundtable, 1984; Rowe et al., 2007; Souza & Powers, 2009). Therefore, strength coaches commonly employ exercises to strengthen the gluteus maximus musculature of their athletes (Duehring et al., 2009; Ebben & Blackard, 2001; Ebben et al., 2004; Ebben et al., 2005; Simenz et al., 2005). Two frequently prescribed exercises for strengthening the gluteus maximus are the back squat and barbell hip thrust.

The knee extensors have been shown to be the largest contributors (49%) to vertical jump performance (Hubley & Wells, 1983), while hip extensor and knee flexor muscles have been shown to increase the most in relative muscle force contribution as running speed progresses towards maximum (Dorn et al., 2012; Schache et al., 2011). Therefore, the quadriceps and hamstrings also are of great importance for maximizing performance in sports that are reliant upon running prowess.

The back squat is perhaps one of the most studied and utilized closed kinetic chain exercises and is a staple in strength and conditioning programs aimed at

strengthening both the lower body in general and the gluteus maximus in particular. Numerous studies have investigated gluteus maximus electromyography (EMG) activity in the back squat, as reported in a recent review (Clark et al., 2012). These researchers found that: increasing stance width and hip rotation in the back squat led to increased gluteus maximus and adductor activity; back squat depth past parallel does not significantly alter muscle activity assuming identical relative loading is used; leg and trunk muscle activity increase with increasing load; and the highest muscle activation occurs in the initial portion of the concentric phase of movement.

However, there is a paucity of data comparing gluteus maximus EMG activity in the back squat to that of other barbell exercises that target this muscle (Clark et al., 2012). The back squat is also commonly used in strength and conditioning programs for increasing sprint-running ability. Its usage for this purpose is supported by a recent meta-analysis in which the back squat was shown to transfer positively to sprint running performance (Seitz et al., 2014). However, large increases (~23–27%) in back squat 1 RM are necessary for significant changes in sprint times (~ –2–3%) in recreationally trained athletes and collegiate football players (Cronin, Ogden, & Lawton, 2007; Jacobson, Conchola, Glass, & Thompson, 2013). Given this relatively low transfer effect, it is of interest for sports science researchers to understand the best exercises, methods, and protocols for improving sprint running performance. Since the gluteus maximus and hamstrings are highly activated in sprinting (Bartlett et al., 2014; Dorn et al., 2012; Jonhagen, Ericson, Nemeth, & Eriksson, 1996; Kyrolainen et al., 2005; Schache, Kim, Morgan, & Pandy, 2010), it would be reasonable to assume that exercises that activate the gluteus maximus and hamstrings to a greater degree than other exercises may be better suited for increasing the strength of those muscles, and thus, sprinting speed.

The barbell hip thrust, first introduced in the literature by Contreras et al. (2011), is another exercise aimed at strengthening the gluteal musculature. To date, no acute or longitudinal studies have investigated the barbell hip thrust or its effects on gluteus maximus EMG activity, strength, sprint running speed, or gluteal development, nor has it been compared to the back squat.

The purpose of this investigation was to compare lower body muscle EMG activity between the back squat and barbell hip thrust. Since previous investigations have revealed that one, the gluteus maximus has at least three functional subdivisions proximally to distally, and two, that the upper and lower portions of the gluteus maximus have been shown to activate uniquely during stair ambulation and prone hip extension at varying levels of hip abduction (Fujisawa et al., 2014; Lyons et al., 1983; McAndrew et al., 2006), muscle activity was recorded for both the upper and lower gluteus maximus. First, due to the findings of Worrell et al. (2001), showing that gluteus maximus EMG was greater during MVICs in full hip extension compared to hip flexion, it was hypothesized that the barbell hip thrust would elicit greater upper and lower gluteus maximus EMG activity compared to the back squat in both dynamic and isometric conditions. Second, on the basis of previous studies showing that the back squat elicited high levels of quadriceps EMG activity but low levels of hamstrings EMG activity (Ebben et al., 2009), it was hypothesized that the back squat would elicit greater vastus lateralis EMG activity and less biceps femoris EMG activity compared to the barbell hip thrust in both dynamic and isometric conditions.

7.2 Methods

A convenience sample of thirteen healthy women (age = 28.9 ± 5.11 years; height = 164 ± 6.26 cm; body mass = 58.2 ± 6.37 kg) participated in this study. Subjects had 7.00 ± 5.80 years of resistance training experience and had a 10 RM of 53.2 ± 17.0 kg

and 87.4 ± 19.3 kg on the back squat and barbell hip thrust, respectively. Inclusion criteria required subjects to be between 20 to 40 years of age, have at least three years of consistent resistance training experience, and be familiar with performance of both the back squat and barbell hip thrust exercises. All subjects were healthy and free of any musculoskeletal or neuromuscular injuries, pain, or illnesses. Subjects filled out an Informed Consent and Physical Activity Readiness Questionnaire (PAR-Q). Any subject that answered “yes” to any of the questions on the PAR-Q was excluded. Subjects were advised to refrain from training their lower body for 72 hours prior to testing. To ensure acceptable performance in the back squat and barbell hip thrust, subjects performed each movement using only a barbell while the lead researcher evaluated technique. If a subject reported pain, discomfort, or failed to perform the movement correctly, she was excluded from participation. If, for any reason, a subject could not complete a trial, her data was discarded. The study was approved by the Auckland University of Technology Ethics Committee.

Subjects first performed a 10-minute general warm-up consisting of various dynamic stretches for the lower body musculature. Afterwards, three progressively heavier specific warm-up sets were performed for both the back squat and barbell hip thrust exercises. Next, each subject performed as many repetitions as she could with a moderately heavy load that could not be performed for more than 10 repetitions. Subjects’ 1 RMs were then estimated by utilizing information provided by Baechle and Earle (2008). Finally, subjects’ 10 RMs were estimated using the aforementioned table, which corresponded to 75% of the subjects’ 1 RM. This approach is similar to that used by Vigotsky et al. (2015). The order of the testing was randomized.

Subjects were asked to wear appropriate clothing for access to the EMG electrode placement sites. Before placing the electrodes on the skin, excess hair was removed with a razor, and skin was cleaned and abraded using an alcohol swab. After

preparation, self-adhesive disposable silver/silver chloride pre-gelled dual snap surface bipolar electrodes (Noraxon Product #272, Noraxon USA Inc, Scottsdale, AZ) with a diameter of 1 cm and an inter-electrode distance of 2 cm were attached in parallel to the fibers of the right upper gluteus maximus, lower gluteus maximus, biceps femoris, and vastus lateralis in concordance with the recommendations of Lyons et al. (1983), Hermens et al. (1999), and Fujisawa et al. (2014). In particular, the upper gluteus maximus electrodes were placed superior and lateral to a line drawn between the PSIS and the posterior greater trochanter, and the lower gluteus maximus electrodes were placed Inferior and medial to a line drawn between the PSIS and the posterior greater trochanter. After the electrodes were secured, a quality check was performed to ensure EMG signal validity.

Ten minutes after 10 RM testing, maximum voluntary isometric contraction (MVIC) testing was performed. For the gluteus maximus, two MVIC positions were tested. The first involved a prone bent-leg hip extension against manual resistance applied to the distal thigh, as utilized by Boren et al. (2011), and the second involved a standing gluteal squeeze. Pilot data from our lab revealed that a minority of subjects achieved higher levels of gluteus maximus EMG activity with the standing gluteal squeeze than during the prone bent-leg hip extension against manual resistance. Thus, both conditions were recorded and EMG was normalized to whichever contraction elicited greater EMG activity. Biceps femoris MVIC was determined by having the subject lay prone and produce maximum knee flexion torque at 45° knee flexion against manual resistance applied to the distal leg just above the ankle, as reported by Mohamed et al. (2002). Two vastus lateralis MVIC positions were used. The first had the subject sit and produce maximum knee extension torque against manual resistance applied to the distal leg just above the ankle at 90° hip flexion and 90° knee flexion, as detailed by Kong and Van Haselen (2010), while the second used a 90° hip flexion and

180° knee position. Whichever contraction elicited greater EMG activity was used for normalization. In all MVIC positions, subjects were instructed to contract the tested muscle “as hard as possible”.

After 10 minutes of rest following MVIC testing, subjects performed 10 repetitions utilizing their estimated 10 RM of the back squat and the barbell hip thrust in a randomized order and counterbalanced fashion. During the back squat, subjects’ feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. Subjects descended until the tops of the thigh were parallel with the floor (Figure 7.1) (Pierce, 1997). In accordance with Contreras et al. (2011), the barbell hip thrust was performed by having subjects’ upper backs on a bench, approximately 16 inches high. Subjects’ feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. The barbell was padded with a thick bar pad and placed over the subjects’ hips. The subjects were instructed to thrust the bar upwards while maintaining a neutral spine and pelvis (Figure 7.2). Subjects were given five minutes of rest between sets. No pre-determined tempo was set as to better mimic typical training conditions.

Following 10 minutes of rest, subjects then performed three-second isoholds for the back squat and barbell hip thrust exercises using the same estimated 10RM loads as they did during the dynamic tests. Order was randomized in a counterbalanced fashion and depth was set at parallel (in hip flexion) for the back squat and at lockout (at full hip extension) for the barbell hip thrust. Subjects were given five minutes of rest between sets.



Figure 7.1. Back squat form.



Figure 7.2. Hip thrust form.

Raw EMG signals were collected at 2000 Hz by a Myotrace 400 EMG unit (Noraxon USA Inc., Scottsdale, AZ). Data was sent in real time to a computer via Bluetooth and recorded and analyzed by MyoResearch 3.6 Clinical Applications

software (Noraxon USA, Inc., Scottsdale, AZ). Signals of all 10 repetitions for the dynamic sets and for all three seconds of the isoholds were first filtered using a 10-500 Hz bandpass filter, followed by full-wave rectification and smoothing using root mean square (RMS) with a 100 ms window. Finally, mean and peak data were normalized to a mean peak of a 1000 ms window from the MVIC trials.

Paired samples *t*-tests were performed using SPSS (Version 22.0, IBM Corp., Armonk, NY, USA). Alpha was set to 0.05 for significance, and a Holm-Bonferroni correction was used to correct for multiple pairwise comparisons for each muscle tested. Adjusted *p*-values were reported. Effect sizes (ES) were calculated by Cohen's *d* using the formula $M_1 - M_2 / SD$, where means (M) from each group (back squat and barbell hip thrust) were subtracted and divided by the pooled standard deviation (SD). ES were defined as small, medium, and large for 0.20, 0.50, and 0.80, respectively (Cohen, 1988). Confidence intervals (95% CI) for each ES were also calculated.

7.3 Results

The barbell hip thrust elicited significantly greater mean (ES = 1.55; 95% CI = 0.63 – 2.37; *p* < 0.004) and peak (ES = 1.22; 95% CI = 0.35 – 2.02; *p* = 0.004) upper gluteus maximus; mean (ES = 1.64; 95% CI = 0.70 – 2.47; *p* = 0.004) and peak (ES = 1.18; 95% CI = 0.31 – 1.97; *p* = 0.038) lower gluteus maximus; and, mean (ES = 1.58; 95% CI = 0.66 – 2.41; *p* = 0.004) and peak (ES = 1.63; 95% CI = 0.69 – 2.45; *p* < 0.004) biceps femoris EMG activity than the back squat. There were no significant differences in mean (ES = -0.15; 95% CI = -0.91 – 0.63; *p* = 0.531) and peak (ES = -0.17; 95% CI = -0.94 – 0.60; *p* = 0.400) vastus lateralis EMG activity between the back squat and barbell hip thrust exercises (Table 7.1).

The barbell hip thrust isohold elicited significantly greater mean (ES = 1.36; 95% CI = 0.47 – 2.17; *p* = 0.004) and peak (ES = 1.37; 95% CI = 0.47 – 2.17; *p* =

0.004) upper gluteus maximus; mean (ES = 2.61; 95% CI = 1.50 – 3.56; $p < 0.001$) and peak (ES = 2.44; 95% CI = 1.36 – 3.36; $p < 0.001$) lower gluteus maximus; and, mean (ES = 1.66; 95% CI = 0.72 – 2.49; $p = 0.001$) and peak (ES = 1.63; 95% CI = 0.70 – 2.46; $p = 0.001$) biceps femoris EMG activity than the back squat isohold. There were no significant differences in mean (ES = -0.25; 95% CI = -1.01 – 0.53; $p = 0.230$) and peak (ES = -0.18; 95% CI = -0.94 – 0.60; $p = 0.389$) vastus lateralis EMG activity between the back squat and barbell hip thrust isoholds (*Table 7.1*).

Table 7.1. Mean (\pm SD) and peak EMG amplitudes (% MVIC) of the upper gluteus maximus, lower gluteus maximus, biceps femoris, and vastus lateralis during the barbell hip thrust and back squat.

		Upper Gluteus Maximus	Lower Gluteus Maximus	Biceps Femoris	Vastus Lateralis
Mean	Back Squat	29.4 \pm 16.5	45.3 \pm 23.5	14.92 \pm 6.64	110 \pm 47.2
	Barbell Hip Thrust	69.5 \pm 32.6 *	86.8 \pm 27.0 *	40.8 \pm 22.1 *	99.5 \pm 92.3
Peak	Back Squat	84.9 \pm 42.9	130 \pm 60.5	37.5 \pm 18.4	244 \pm 122
	Barbell Hip Thrust	1712 \pm 91.0 *	216 \pm 83.8 *	86.9 \pm 38.8 *	216 \pm 194
Iso Mean	Back Squat	10.1 \pm 7.96	20.9 \pm 20.0	7.38 \pm 4.28	134 \pm 108
	Barbell Hip Thrust	87.1 \pm 79.4 *	116 \pm 47.4 *	42.5 \pm 29.6 *	111 \pm 78.3
Iso Peak	Back Squat	17.9 \pm 17.0	34.3 \pm 32.8	13.73 \pm 9.99	201 \pm 163
	Barbell Hip Thrust	128 \pm 113 *	180 \pm 78.2 *	67.7 \pm 45.8 *	176 \pm 124

* Denotes a statistically significant difference from the back squat ($p \leq 0.05$).

Statistically significantly greater EMG activity was observed in the barbell hip thrust for mean, peak, iso mean, and iso peak upper gluteus maximus, lower gluteus maximus, and biceps femoris when compared to the back squat.

7.4 Discussion

Results partially confirm the research hypotheses in that the barbell hip thrust elicited significantly greater gluteus maximus (upper mean ES: 1.55; upper peak ES: 1.22; lower mean ES: 1.64; lower peak ES: 1.18) and biceps femoris (mean ES: 1.58; peak ES: 1.63) EMG activity than the back squat. However, the back squat failed to elicit

significantly greater vastus lateralis (mean ES: -0.15; peak ES: -0.17) EMG activity than the barbell hip thrust.

It was not surprising that the barbell hip thrust elicited significantly greater gluteus maximus EMG activity than the back squat, both when assessed dynamically and during isoholds. Worrell et al. (2001) described the EMG hip angle relationship of the gluteus maximus during MVICs. Their data showed that when creating maximal isometric hip extension torque in an isokinetic dynamometer at 90°, 60°, 30°, and 0° hip angles, gluteus maximus EMG activity was lowest with the hip in 90° of hip flexion and highest with the hip in 0° of hip extension (neutral). Furthermore, because the knee is flexed during the barbell hip thrust, it is presumed that the hamstrings are under active insufficiency, thus requiring greater muscular effort from the gluteus maximus in order to generate sufficient hip extension torque. Since muscular effort appears to be greatest during the barbell hip thrust when the hips are in full extension but greatest in the back squat when the hips are in flexion (Bloomquist et al., 2013; Bryanton et al., 2012; Contreras et al., 2011), it is logical that gluteus maximus EMG activity is greater during the barbell hip thrust than during the back squat. These results are especially pertinent to our findings in that during the isometric barbell hip thrust, the hips are in full extension, allowing for exceptionally high levels of upper and lower gluteus maximus EMG activity (upper = 87.1; lower = 116%), but during the isometric back squat, the hips are in flexion, and therefore, not as much gluteus maximus EMG activity (upper = 10.1%; lower = 20.9%) can be elicited. Prior to data collection, we recorded extensive pilot data which showed that the gluteus maximus EMG angle relationship is remarkably predictable in multiple isometric testing positions, including MVICs performed during squat, deadlift, lunge, hip thrust, reverse hyper, back extension, and quadruped hip extension exercise positions at varying hip angles along the hip flexion/extension axis, with and without applied manual resistance. It appears that the

shorter the muscle length, the greater the potential levels of gluteus maximus EMG activity. As noted by Robertson et al. (2008), gluteus maximus EMG activity reached a minimum at the bottom of the eccentric phase of the back squat, where the muscle length reaches its maximum, even though Caterisano et al. (2002) noted greater gluteus maximus activity in full depth squats than in parallel and partial squats. However, Caterisano et al. (2002) did not utilize relative loading, which may explain why greater EMG activity was observed in the full depth squat than the parallel and partial squats (Clark et al., 2012). Though the data for the back squat isohold was congruent with that of Schaub and Worrell (1995), there were two key differences between their study and the present study. First, the squat depth used by Schaub and Worrell (1995) was more shallow, and second, participants performed an overcoming isohold which involved maximally pushing against an immovable crossbar, whereas this study utilized a yielding isohold where subjects held a 10 RM load in place.

Similarly, it was not surprising that the barbell hip thrust (dynamic = 40.8%; isometric = 42.5) elicited significantly greater biceps femoris EMG activity than the back squat (dynamic = 14.9%; isometric = 7.38%), both when assessed dynamically and during isoholds. Numerous studies have found that the back squat routinely displays low levels of hamstrings EMG activity, especially in comparison with measurements taken from the quadriceps (Escamilla, Fleisig, Zheng, et al., 2001; Isear, Erickson, & Worrell, 1997; McCaw & Melrose, 1999; Paoli et al., 2009), although some of these studies did not normalize EMG measurements (McCaw & Melrose, 1999; Paoli et al., 2009), which makes direct comparison between muscles difficult. Exactly why the back squat leads to low levels of EMG activity in the hamstrings is not entirely clear. It may relate to the biarticular nature of the hamstrings musculature. While the squat involves hip extension, for which the hamstrings are a prime mover, it also involves knee extension, for which the hamstrings are an antagonist. Yamashita

(1988) compared hamstrings EMG activity during isolated hip extension and isolated knee extension movements performed with 20% of the MVIC moment to hamstrings EMG activity with a combined hip and knee extension movement using the same hip and knee extension moments. Hamstrings EMG activity in combined hip and knee extension only reached 42% of the level in the isolated hip extension movement despite the hip extension moment being identical in each case. It was concluded that hamstrings EMG activity was depressed when combined hip and knee extension were performed compared to during isolated hip extension. This may occur because the hamstrings changed length to a greater extent when performing isolated hip extension compared to when performing combined hip and knee extension. Kwon and Lee (2013) noted that the maximum hip extension torque and hamstrings EMG decreased at knee flexion angles greater than 60°, indicating that hamstring activity was markedly reduced when the knee was significantly bent.

In contrast, the failure of the back squat to display greater vastus lateralis EMG activity in comparison with the barbell hip thrust was unexpected. The back squat is well known to elicit high levels of quadriceps EMG activity in comparison with other lower body exercises, including the leg press and leg extension (Wilk et al., 1996) and the Smith machine squat (Schwanbeck et al., 2009). Thus, the failure of our trial to discern any statistical difference in vastus lateralis EMG activity between the barbell hip thrust and the back squat deserves further investigation, particularly as the risk of type I error during post-hoc testing was managed by the use of the Holm-Bonferroni correction (Holm, 1979) rather than the more conservative Bonferroni correction (Armstrong, 2014; McLaughlin & Sainani, 2014). It may be that the different quadriceps muscles display different levels of EMG activity during the barbell hip thrust, with the vastus lateralis being unusually highly activated. Or perhaps heavier loads than the estimated 10 RMs used in this study would have lead to significant

differences in vastus lateralis activation. Alternatively, the barbell hip thrust may require very high levels of quadriceps co-contraction in order to stabilize the knee joint.

Caution should be taken when interpreting the practical implications of this study. It is tempting to speculate that muscle activity can be used as a gauge to predict strength and hypertrophy gains. After all, two recent papers have linked muscle activation with hypertrophy (Wakahara et al., 2013; Wakahara et al., 2012), and another with strength gains (Calatayud et al., 2014). However, at this point in time, no training studies have been conducted comparing the hypertrophic effects or transfer of training in the back squat and barbell hip thrust exercises. Future research needs to be conducted to: one, test the hypothesis that the barbell hip thrust exercise leads to greater gluteus maximus and hamstring hypertrophy than does the back squat exercise; two, discern whether adaptations transfer to sports performance, particularly in relation to sprint running; three, verify that male and female subjects activate their hip and thigh muscles similarly during the back squat and barbell hip thrust exercises; and four, analyze the joint range of motion, heart rate, force, power, joint power, and torque angle curves between the back squat and barbell hip thrust exercises.

Comparing results between EMG studies can be problematic. At the very least, for comparative analysis, two studies would need to have the same electrode site placements, MVIC positions, data processing and amplitude presentation, exercise form, resistance load, tempo, and effort, and exercise range of motion. This is rarely the case with EMG studies examining resistance training exercises. In addition, gender, age, and training age might influence the comparability between EMG studies as well. The various back squat EMG studies that have normalized EMG to MVIC can be observed in Table 7.2. When examining the table, it is apparent that there are broad differences in EMG results between the studies, but these discrepancies can be explained when considering the aforementioned variables. For example, the studies

utilized different electrode site placements, MVIC positions, loads, and ranges of motion, and they presented the amplitude differently as well. An in depth discussion of EMG variables is beyond the scope of this article. For a closer investigation of the muscle activation during the back squat exercise, one is directed to a recent review article by Clark et al. (2012). When considering the aforementioned variables, the findings of this study are in line with previous research (Table 7.2).

Table 7.2. EMG findings of previous research on the back squat for the gluteus maximus, biceps femoris, and vastus lateralis muscles compared to current findings.

	Load	Gluteus Maximus EMG	Biceps Femoris EMG	Vastus Lateralis EMG
Gullett et al. (2009)	70% of 1RM	n/a	~20% mean	~65% mean
Wilk et al. (1996)	12RM	n/a	36% mean	54% peak
Escamilla et al. (1998)	12RM	n/a	~ 90% peak	~ 80% peak
Manabe et al. (2007)	30% of 1RM	~ 80% peak	~ 40% peak	~ 60% peak
Escamilla, Fleisig, Zheng, et al. (2001)	12RM	n/a	41% peak	57% peak
Aspe and Swinton (2014)*	75% of 1RM	~ 55% mean	~ 50% mean	~ 76% mean
Ebben et al. (2009)	6RM	n/a	32% mean	91% mean
Contreras et al.	10RM	45% mean 130% peak **	15% mean 38% peak	110% mean 244% peak

* Utilized integrated EMG, average of the eccentric and concentric phases is presented

** Represents lower gluteus maximus data, as it was assumed that it might better represented how the middle gluteus maximus fibers would activate when compared to the upper gluteus maximus fibers.

Limitations of this study should be considered when interpreting the findings of this study. Firstly, surface EMG is sensitive to things like neighboring crosstalk, sliding of the skin over the muscle belly, and changes in muscle belly geometry. An estimated 10 RM was utilized, which may differ from subjects' actual 10 RM, possibly due to the fact that the methods described by Baechle and Earle (2008) have not been validated in the hip thrust or back squat. Moreover, if the subjects could have performed extra repetitions during testing above their estimated 10 RMs, we did not have them do so. Therefore, exercise testing was not carried out to momentary muscular failure for each exercise. Finally, relatively light loads were used in this study. Fairly linear

relationships between load and EMG activity have been observed in exercises such as the good morning (Vigotsky et al., 2015) and back squat (Aspe & Swinton, 2014), though no such relationship has been established with the barbell hip thrust exercise. Therefore, the results of this study only apply to loads of approximately 75% of 1 RM, or around a 10 RM.

The back squat has long been a staple in strength training programs and is one of the most well researched exercises in the literature. The barbell hip thrust is a newer exercise that lacks longitudinal research. Fitness professionals can confidently incorporate back squats into their programs with the knowledge that they will lead to hypertrophy and performance improvements. The findings of this study indicate that fitness professionals can also justify the inclusion of barbell hip thrusts into their programming for developing the hip extensor musculature due to the superior mean and peak gluteus maximus and biceps femoris activity compared to the back squat. In cases where back squats cannot safely be performed, perhaps due to injury, pain, mobility deficits, or hip dysfunction, the greater stability of the barbell hip thrust would seem to make it an excellent alternative for developing the lower body musculature. Additionally, evidence suggests that individuals seeking to maximize their gluteus maximus development should incorporate barbell hip thrusts into their regimen.

***KINETIC ANALYSIS OF THE BACK SQUAT AND BARBELL HIP
THRUST EXERCISES***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**Journal of Applied Biomechanics
In Review (Appendix 4h)**

8.0 Prelude

The previous chapter examined EMG activity between squats and hip thrusts. However, no research currently exists comparing squats and hip thrusts in force-time data. Since variables such as force, impulse, work, and power are thought to be important for strength, hypertrophy, and power adaptation, it is important to explore these variables in relation to the squat and hip thrust. If one exercise was found to be highly superior to another in one or more of the variables of interest, this could mean that it is better suited for eliciting adaptations favorable to improved performance. This chapter sought to kinetically compare squats to hip thrusts in measures of force, work, impulse, and power.

8.1 Introduction

There is a strong body of literature elucidating that force-time characteristics of exercise and movements in sport are important determinants for the performance of various strength and explosive movements. For example, peak force applied at the time of maximum rate of force development is a strong determinant of countermovement jump performance (Marques et al., 2015), and by modifying the load, one can alter jump squat performance or force-time characteristics (Cormie, McBride, & McCaulley, 2008).

With regards to resistance training, the force-time characteristics of numerous exercises have been described, including, but not limited to: squats, cleans, kettlebell swings, deadlifts, and bench press (Bloomquist et al., 2013; Comfort, Allen, et al., 2011b; Drinkwater, Moore, & Bird, 2012; Garcia-Masso et al., 2011; Israetel, McBride, Nuzzo, Skinner, & Dayne, 2010; Lake & Lauder, 2012; Lake, Mundy, & Comfort, 2014; Pearson, Cronin, Hume, & Slyfield, 2009; Swinton, Lloyd, et al., 2012; Swinton,

Stewart, Agouris, et al., 2011; Swinton, Stewart, Keogh, Agouris, & Lloyd, 2011; Swinton, Stewart, et al., 2012). Such characteristics include power, impulse, force, and rate of force development. In some cases, it may be important to divide such characteristics into the concentric and eccentric phases, due to the force-velocity relationship of muscle (Cronin, McNair, & Marshall, 2003; Cuk et al., 2014). More specifically, muscle can generate more force at greater velocities during an eccentric action, but the opposite is true for concentric actions. Furthermore, different phases may have different levels of importance for determining performance. For example, the eccentric portion of a vertical jump does not contribute to the vertical impulse that determines take-off velocity, and ultimately, jump height, but it may help to control hip flexion via an eccentric action during tasks like sprinting.

There are three calculated kinetic variables of interest; work, power, and impulse. Work (W) is the dot product of force and displacement (Eq. 1) and may be used to determine the economy of an exercise (Kalb & Hunter, 1991; Shaner et al., 2014). Power (P) is the rate at which work is performed, or the dot product of force and velocity, and is of especial importance in explosive movements (Cronin, McNair, & Marshall, 2001; Kawamori & Haff, 2004). When calculating power, it is important to normalize to, or divide by, mass, as including it can significantly alter the load-power relationship (Blatnik et al., 2014; Cormie, McBride, & McCaulley, 2007). Finally, impulse (J) is the product of force and time, or the change in momentum (Eq. 3). Impulse is especially useful in determining athletic performance, as when divided by system mass, it equals the change in velocity of the body in question (Kirby, McBride, Haines, & Dayne, 2011; Lake, Carden, & Shorter, 2012; Lake, Hetzler, & Lauder, 2014; Moir, Graham, Davis, Guers, & Witmer, 2013). This makes impulse ideal for predicting things like vertical jump height. Furthermore, unlike work and power,

impulse is a vector quantity, meaning that its directional components can be separated and reported as such.

$$W = \vec{F} \cdot \vec{d} \quad (\text{Eq. 1})$$

$$P = \frac{dW}{dt} = \vec{F} \cdot \vec{v} \quad (\text{Eq. 2})$$

$$\vec{J} = \int \vec{F} dt = \Delta \vec{p} \quad (\text{Eq. 3})$$

The hip thrust, described by Contreras et al. (2011), is a new exercise that utilizes a horizontal force vector relative to the exerciser's body. On a force plate, this horizontal force vector is represented as the vertical ground reaction force due to the exercise's supine positioning. Because horizontal force has been found to be more important than vertical for sprint performance (Morin et al., 2011), it is possible that such an exercise will improve sprinting ability to a greater extent than will popular axial-loaded lower body exercises, even though the squat has recently been shown in a meta-analysis to improve sprint performance (Seitz et al., 2014). Previous work from our group has compared the EMG activity in the hip thrust to that of the squat, though the kinetics of these two exercises have not yet been compared (Contreras et al., 2015a). Therefore, the purpose of this study is to compare average vertical force throughout the entire lift, average vertical force during the concentric and eccentric phases, average power, total work, total impulse, and bar displacement between the squat and hip thrust. Greater loads are typically used in the hip thrust compared to the squat (Contreras et al., 2015a), and since mass heavily influences force, and force heavily influences impulse, work, and power, it is hypothesized that the hip thrust will outperform the squat in all measures except bar displacement and total time, in which the squat will have an advantage.

8.2 Methods

A convenience sample of ten healthy male subjects (age = 27.0 ± 4.8 years; height = 1.77 ± 0.04 m; body mass = 86.4 ± 13.8 kg) participated in this study. Subjects had 6.9 ± 4.2 years of resistance training experience and had a 10R M of 98.0 ± 20.4 kg and 114 ± 35.5 kg on the back squat and barbell hip thrust, respectively. Inclusion criteria required subjects to be between 18 and 35 years of age, have at least three years of consistent resistance training experience, and be familiar with performance of both the back squat and barbell hip thrust exercises. All subjects were healthy and free of any musculoskeletal or neuromuscular injuries, pain, or illnesses. Subjects filled out an Informed Consent and Physical Activity Readiness Questionnaire (PAR-Q). Any subject that answered “yes” to any of the questions on the PAR-Q was excluded. Subjects were advised to refrain from training their lower body for 72 hours prior to testing. To ensure acceptable performance in the back squat and barbell hip thrust, subjects performed each movement using only a barbell while the lead researcher evaluated technique. If a subject reported pain, discomfort, or failed to perform the movement correctly, he was excluded from participation. If, for any reason, a subject could not complete a trial, his data was discarded. The study was approved by the Auckland University of Technology Ethics Committee.

Subjects first performed a 10-minute general warm-up consisting of various dynamic stretches for the lower body musculature. Afterwards, three progressively heavier specific warm-up sets were performed for both the back squat and barbell hip thrust exercises. Next, each subject performed as many repetitions as he could with a moderately heavy load that could not be performed for more than 10 repetitions. Subjects' 1 RMs were then estimated by utilizing information provided by Baechle and Earle (2008). Finally, subjects' 10 RMs were estimated using the aforementioned table,

which corresponded to 75% of the subjects' 1 RM. This approach is similar to that used by Vigotsky et al. (2015). The order of testing was randomized.

Ten minutes after 10 repetition testing, subjects performed 10 repetitions utilizing their estimated 10 RM of the back squat and the barbell hip thrust in a randomized order and counterbalanced fashion. During the back squat, subjects' feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. Subjects descended until the tops of the thigh were parallel with the floor (Figure 8.1) (Pierce, 1997). In accordance with Contreras et al. (2011), the barbell hip thrust was performed by having subjects' upper backs on a bench, approximately 38 cm high with a 2 cm pad. Subjects' feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. The barbell was padded with a thick bar pad and placed over the subjects' hips. The subjects were instructed to thrust the bar upwards while maintaining a neutral spine and pelvis (Figure 8.1). Subjects were given 10 minutes of rest between sets. No pre-determined tempo was set as to better mimic typical training conditions.



Figure 8.1. Performance of the hip thrust (left) and parallel squat (right) on the force plate.

Subjects were instructed to “hover” on a Bertec instrumented treadmill (Bertec, Columbus, OH) with the load before beginning. This process was used to tare the force plate so that system weight could be subtracted from the proceeding trial. A 9-camera Vicon 3D camera system was used to capture bar displacement via retroreflective markers placed on the center of the left and right ends of the barbell. Data were collected at 1000Hz and 200Hz, for the force plate and motion capture, respectively. Data, unfiltered, were then reduced in Visual3D (Qualisys AB, Gothenburg, Sweden).

Movement was divided according to when the bar started to move, when the bar reached maximal/minimal position, and then when the bar stopped moving to give the concentric and eccentric phases of the movement. Between-repetition periods were removed. Impulse was calculated via the trapezoid method to find the area under the force-time curve. Work was calculated via the trapezoid method to find the area under the force-bar displacement curve. Repetition time was calculated as the time from when the bar initiated movement until the end of the movement. Work was then divided by repetition time to find average power.

All data were entered into Stata (StataCorp, College Station, TX), wherein Shapiro-Wilk tests were performed to ensure normality. Paired samples *t*-tests were performed. Alpha was set to 0.05, and the Benjamini-Hochberg procedure was used to correct for false discovery rate (Benjamini & Hochberg, 1995). Adjusted p-values were reported. Effect sizes (ES) were calculated by Cohen’s *d* using the formula $d = \frac{M_d}{s_d}$, where s_d is the standard deviation of differences. This method is slightly different than the traditional method of calculating Cohen’s *d*, as calculates the within-subject effect-size rather than group or between-subject effect size. Cohen’s *d* was defined as small, medium, and large for 0.20, 0.50, and 0.80, respectively (Cohen, 1988). Ninety-five percent confidence limits (95% CL) for effect sizes were also calculated.

8.3 Results

All but one subject's data were included in the analysis, as that subject's hip thrust trial file was corrupted. Furthermore, one subject only performed nine repetitions of the squat due to a miscount. All data were found to be parametric. Paired-samples *t*-tests revealed that the greater levels of bar displacement ($p = 0.000$; $d = 5.59$ (4.83, 6.36)) in the back squat were not due to chance alone. However, no statistically significant differences were observed in mean force ($p = 0.360$; $d = 0.36$ (−0.41, 1.13)), total impulse ($p = 0.067$; $d = 1.00$ (0.23, 1.77)), total work ($p = 0.223$; $d = 0.51$ (−0.26, 1.28)), total time ($p = 0.068$; $d = 0.86$ (0.09, 1.63)), average power ($p = 0.766$; $d = 0.10$ (−0.67, 0.87)), average concentric force ($p = 0.252$; $d = -0.48$ (−1.25, 0.29)), and average eccentric force ($p = 0.068$; $d = 0.85$ (0.08, 1.62)) (Table 8.1).

Table 8.1. Comparison between the vertical kinetics of the back squat and hip thrust.

	Back Squat	Hip Thrust	Percent Difference	Effect size (95% CL)
Bar Displacement (m)	0.66 ± 0.03 *	0.37 ± 0.03	57.5%	5.59 (4.83, 6.36)
Total Work (J)	1010 ± 568	674 ± 348	39.9%	0.51 (−0.26, 1.28)
Total Time (s)	22.1 ± 2.33	18.0 ± 3.87	20.3%	0.86 (0.09, 1.63)
Average Power (W)	48.3 ± 30.0	43.4 ± 33.6	10.6%	0.10 (−0.67, 0.87)
Total Impulse (N.s)	2522 ± 906	1570 ± 385	46.5%	1.00 (0.23, 1.77)
Average Force (N)	118 ± 50.5	94.5 ± 42.6	22.4%	0.36 (−0.41, 1.13)
Average Concentric Force (N)	126 ± 54.3	158 ± 63.0	22.5%	−0.48 (−1.25, 0.29)
Average Eccentric Force (N)	112 ± 47.6	56.5 ± 32.6	65.5%	0.85 (0.08, 1.62)

* = difference is not due to chance alone ($p \leq 0.05$).

8.4 Discussion

The proposed hypotheses were rejected for all measures except bar displacement, in which the squat was greater than the hip thrust ($p \leq 0.05$). The significant difference

(57.5%; ES = 5.59 (4.83, 6.36)) in the displacement measure was obviously explained by the reduced range of motion associated with the hip thrust.

As the back squat required nearly twice the linear range of motion than that of the hip thrust (57.5% difference), this no doubt was one reason for the large differences (39.9%) in work between the exercises, as work is equal to the product of force and displacement. If the movements were normalized by displacement, then the hip thrust would be found to produce approximately 100 J more than the squat, i.e., greater work associated with the same relative range of motion.

As expected, with greater range of motion, the contraction times were greater (20.3%) with the squat. It might be expected therefore that greater power output might be associated with the hip thrust given shorter contraction times because power is equal to work divided by time. However, the slightly shorter repetition time in the hip thrust was not great enough to overcome the differences in work, which resulted in greater ($p > 0.05$) power output in the squat (10.6% difference).

The greater ($p > 0.05$) impulse in the squat (46.5% difference) is likely due to the larger displacement, and in turn, contraction times associated with the increased range of motion of the squat. Interestingly, if the squat was normalized by time, the squat movement would still result in ~ 500 N·s greater impulse than the hip thrust. This is difficult to explain given the small (ES = 0.36) differences in average force between the exercises. However, it needs to be remembered that impulse is calculated from the area under the force-time curve.

Small to large nonsignificant differences were observed in the eccentric and concentric forces associated with each exercise. Of interest, however, was the within-exercise comparison between eccentric and concentric force. The squat's eccentric force output is only 11.1% less than its concentric force output, but the hip thrust's

eccentric force output is 64.3% less than its concentric force output. A number of other studies have also investigated average, concentric, and eccentric force output during the back squat. However, most of these studies did not subtract system load from the reported values (Crewther, Cronin, & Keogh, 2008; Ebben & Jensen, 2002; Flanagan & Salem, 2007; Mohamad, Cronin, & Nosaka, 2012; Wallace, Winchester, & McGuigan, 2006). One can derive vertical force from the vertical impulses reported by Lake et al. (2012) to find the average force of each phase, and the values for the concentric (126.1 vs. 181.5 N) and eccentric (115.5 vs. 81.4 N) are only slightly different from our findings. These small differences may be due to the load used, as a 10 RM was utilized in this study, and 80% of subjects' 1 RM was used by Lake et al. (2012).

Given the difference in displacement, it would be expected that other measures derived from displacement (work and power) or affected by displacement (impulse as it takes a longer time to travel a larger distance if velocities are similar) would differ significantly. This, however, was not the case. This could most likely explained by the large variability associated with the subject's 10 RM squat and hip thrust values, which in turn affected statistical significance. With a much more homogeneous or better familiarized sample, it is quite likely that the differences would have been statistically significant. Associated with this, it is likely that this study was underpowered. For example, the observed power of total work was only 0.30, despite having a moderate effect size. In actuality, it is likely that the back squat would outperform the hip thrust in a number of measures, including total work, total impulse, total time, and eccentric force, but this cannot be said for certain. Further research is warranted to confirm that this was, in fact, a power issue resulting in a type II error, rather than a true negative finding. Also, by controlling for false discovery rate, it is possible that type II errors were created, but the test used is rather liberal, especially compared to the classically used Bonferroni correction. In addition, this study did not divide all variables into the

eccentric and concentric phases or measure velocity and rate of force development, which likely would have provided greater insight into the differences between squat and hip thrust ground reaction kinetics. It is likely that the hip thrust would outperform the squat in concentric velocity and concentric power, but this cannot be said for certain. Different results would have likely been observed had different loads been used (Flanagan & Salem, 2007). For example, subjects with greater hip thrust experience would move greater loads and hence greater force output would result, which may in turn counteract the greater displacement of the squat. Therefore, the kinematic and kinetic comparisons would be very different. Furthermore, these results cannot be extrapolated to other populations, and to do so, further investigation and replication is required. One needs to be cognizant of this limitation when interpreting the results.

8.5 Practical Applications

This study was the first to examine the force-time characteristics of the squat and hip thrust normalized to system load. The large differences in bar displacement, work, and impulse between the squat and hip thrust may provide athletes and coaches with a rationale to perform squats for greater potential adaptations. However, the concentric-to-eccentric ratio of the hip thrust cannot be ignored, as it may have sport-specific implications for those sports that may benefit from greater concentric contraction force and velocity. Furthermore, there is more to consider than just these variables. For example, torque-angle curves, muscle activation, and especially direction of force vectors should also be taken into account.

***EFFECTS OF A SIX-WEEK SQUAT VERSUS HIP THRUST
PROGRAM ON PERFORMANCE***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley, Jan
Reyneke, Travis McMaster, John Cronin**

**Journal of Strength and Conditioning Research
In Review (Appendix 4j)**

9.0 Prelude

In Chapters 7 and 8, numerous differences were shown to exist between squats and hip thrusts. However, these findings were mechanistic in nature, and longitudinal research is needed to test the original hypotheses. Specifically, it is important to know how the squat and hip thrust compare in terms of improving various strength and power performance measures. If the force vector theory holds true, then the squat would be better suited for improving vertical jumping, front squat strength, and isometric mid-thigh pull strength, whereas the hip thrust would be better suited for improving acceleration, horizontal jumping, and hip thrust strength. This chapter will seek to determine the nature of transfer between the squat and hip thrust on a variety of strength and power tasks in the vertical and horizontal planes.

9.1 Introduction

The barbell hip thrust, introduced in the literature by Contreras et al. (2011), is a loaded bridging exercise used to target the hip extensor musculature against barbell resistance. It has recently been suggested that the barbell hip thrust can enhance speed, horizontal force production, and gluteus maximus hypertrophy (Beardsley & Contreras, 2014; Contreras et al., 2011; de Lacey et al., 2014; Eckert & Snarr, 2014), as the hip thrust requires consistent hip extension moment production throughout its entire range of motion. The consistent hip extension moment requisites of the hip thrust may play a crucial role in transference, as it has been theorized that hip extension moment-angle curves play an important role in transference to performance (Contreras et al., 2013). Furthermore, because the hip thrust is performed such that the load vector is horizontal to the body, it is theorized that it will better transfer to sports that involve horizontal force vectors. Sprinting is an activity of particular interest, as horizontal force, power,

and impulse have strong associations with sprinting speed and acceleration (Brughelli et al., 2011a; Buchheit et al., 2014; Morin et al., 2011). Randell et al. (2010) proposed that training adaptations may be direction-specific, and that horizontally-loaded exercises may transfer better to horizontal force production, and vice versa for vertically-loaded exercises. To date, only one study has investigated the effects of the hip thrust exercise on performance. The hip thrust was incorporated into an intervention program consisting of free sprints, sled towing, single leg exercises, Nordic hamstring curls, and horizontal plyometrics, although very light loads were utilized in the hip thrust (50-70% of bodyweight for 2-3 sets of 6-8 reps) (Mendiguchia et al., 2014). The intervention group displayed superior increases in accelerating sprint running ability (over 5 m) and both concentric and eccentric isokinetic knee flexion force compared to the control group.

The squat is one of the most well-studied and utilized exercises in strength and conditioning. A recent meta-analysis on the squat found that increases in back squat strength transfer positively to sprint performance ($r = -0.77$) (Seitz et al., 2014). These data are not surprising, as relative squat strength has been correlated with sprint performance (Comfort, Bullock, & Pearson, 2012; Requena, Garcia, Requena, de Villarreal, & Cronin, 2011). It is important to note that the hip extension moment requisites of a squat decrease throughout the ascending concentric range of motion (Bloomquist et al., 2013), suggesting that squats might not be as beneficial for developing end-range hip extension strength as exercises that do emphasize such a range of motion. However, the previously described data on the relationship between squat strength and sprinting performance may not be applicable to all athletes. Research on American football players has shown that increases in squat and vertical jump performance are unaccompanied by an increase in speed (Hoffman, Ratamess, & Kang, 2011; Jacobson et al., 2013). Several training studies involving squats have consistently

showed improvements in vertical jump, but all are confounded with additional exercises (Channell & Barfield, 2008; Hoffman, Cooper, Wendell, & Kang, 2004; Otto, Coburn, Brown, & Spiering, 2012; Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005). Due to the vertical load vector of the squat and the horizontal load vector of the hip thrust, it is possible that the hip thrust has better transference to sprinting, whereas the squat has better transference to vertical jump. It should be mentioned that resistance training appears to be comparable to free sprinting, plyometrics, and sleds for improving acceleration. Therefore, weights are an appropriate form of training to improve shorter sprints (Lockie, Murphy, Schultz, Knight, & Janse de Jonge, 2012).

The identification of how different exercises transfer to sport performance is paramount for strength and conditioning exercise selection. The deep front and back squats have both been shown to lead to better vertical jump improvements than do shallow squats (Hartmann et al., 2012). Furthermore, both the front and back squat have been shown to have similar muscle activation and hip moments (Gullett et al., 2009; Yavuz et al., 2015). Electromyography (EMG) data from our lab showed similar results in that there was no difference between front and back squat quadriceps EMG amplitudes (Contreras, Vigotsky, Schoenfeld, Beardsley, & Cronin, 2015b), but in addition, we have found that the hip thrust activated the hip extensor musculature to a greater degree than the back squat (Contreras et al., 2015a).

Research examining specificity has shown that during 1 RM testing, training specificity is a primary factor (Morrissey, Harman, & Johnson, 1995; Wilson et al., 1996). In other words, those more familiar with the 1 RM test or exercise are likely to perform better during that specific 1 RM test. Thus, it is likely that the group training a specific movement will have an advantage during 1 RM testing for that movement. Nagano, Komura, and Fukashiro (2007) described how both horizontal and vertical jumps require similar quadriceps and glutei work, which are both targeted during the

squat and hip thrust (Contreras et al., 2015a). However, the squat utilizes a vertical force vector, while the hip thrust utilizes a horizontal force vector. Because the horizontal jump requires a large amount of both vertical and horizontal impulse (Wu, Wu, Lin, & Wang, 2003), it is unclear as to whether the barbell hip thrust or front squat would be more conducive to increasing horizontal jump performance. However, the vertical jump is solely reliant upon vertical impulse, and therefore, the front squat should lead to greater vertical jump gains. The isometric mid-thigh pull is one measure that appears to have implications for sport performance, during which the preferred angles for the knee and hip are 133° and 138°, respectively (Comfort, Jones, McMahon, & Newton, 2015). It seems logical that the squat would elicit greater gains in isometric mid-thigh pull strength. However, due to its inherent joint angles, the hip thrust may transfer comparably to the squat due to the angle specific hip extension moment requisites of the isometric mid-thigh pull.

The purpose of this study is to investigate the effects of a six-week hip thrust or front squat program on 10 and 20 m sprint times, horizontal jump distance, vertical jump height, isometric mid-thigh pull performance, and 1 RM front squat and hip thrust strength in adolescent males. It is hypothesized that due to the principle of specificity: one, hip thrusts will improve the hip thrust better than the front squat; two, front squats will improve the front squat better than the hip thrust will; three, hip thrusts will transfer to front squats, but not as well as front squats will; four, front squats will transfer to hip thrusts, but not as well as hip thrusts will; five, hip thrusts will improve 10 and 20 m sprint times better than the front squat will, as hip thrusts elicit greater gluteus maximus and hamstrings activation; six, front squats will improve vertical jump better than the hip thrust will, as front squats utilize a vertical load vector and have greater quadriceps activation; seven, both front squats and hip thrusts will improve horizontal jump distance to a similar degree, as the horizontal jump utilizes both vertical and horizontal

force vectors and display similar levels of gluteal and quadriceps activity; and eight, both front squats and hip thrusts will improve the isometric mid-thigh pull to a similar degree, as both the quadriceps and gluteus maximus are heavily relied upon and its a mid-range hip extension position that is worked effectively in both exercises.

9.2 Methods

This was a single-center, double-blinded, parallel-group randomized-controlled trial with equal randomization (1:1). Each group was assigned to perform the hip thrust or squat twice per week for six weeks, for a total of 12 sessions. Performance variables were collected prior to and following the six-week training period.

Eligible participants were all adolescent athletes, ages 14 to 17, and were enrolled in a New Zealand rugby and rowing athlete development program. As per previous literature (Lockie et al., 2012; Spinks, Murphy, Spinks, & Lockie, 2007), an *a priori* power analysis was performed for increases in acceleration ($\alpha = 0.05$; $\beta = 0.80$; Cohen's $d = 0.8$ – 2.44), and it was determined that 28 subjects (14 for each group) would be adequate, and were recruited. All subjects and their legal guardians were required to complete an Informed Consent and Assent forms, and a Physical Activity Readiness Questionnaire (PAR-Q). All subjects were healthy and injury-free at the commencement of training. This study was approved by the Auckland University of Technology Ethics Committee.

On the first day, subjects completed the necessary forms (Informed Consent, Assent, PAR-Q), warmed up, and baseline testing was performed for body mass, height, vertical jump, horizontal jump, and sprinting. On the second day, after a 10-minute lower dynamic warm up, the subjects squat and hip thrust 3 RM were assessed, followed by their isometric mid-thigh pull.

The vertical jump assessment was performed using a Vertec (Jump USA, Sunnyvale, CA, USA) where vertical jump height was determined by calculating the difference between standing reaching height and maximum jump height. The horizontal jump was measured using a tape measure, which was measured from the toes to the heel of the most rearward landing foot. The vertical and horizontal jumps were performed using a countermovement jump with arm swing, as athletes were allowed to flex at the hips, knees, and ankles to a self-selected depth in order to utilize the stretch-shortening cycle during triple extension. Subjects were given three trials for each test, separated by three minutes of rest. The highest and farthest jumps out of the three trials were used for analysis.

Following the vertical and horizontal jump testing, subjects were given 10 minutes rest, before performing a 20 m sprint. Three warm-up 20 m sprint trials at approximately 70, 80, and 90% of maximum sprinting speed were performed prior to testing. Data was collected using single beam timing lights (SmartSpeed, Fusion Sport, Coopers Plains, Australia). All timing lights were set to a height of 60 cm (Cronin, 2008). The subjects were required to start in a split stance 50 cm behind the first set of timing lights. Subjects were given three 20-m sprint trials separated by five minutes. The fastest time out of the three trials was used for analysis. The 0-10 m and 0-20 m split times were used for analysis.

Subjects first performed a 10-minute lower body dynamic warm-up consisting of two sets of 10 repetitions of the following movements: standing sagittal plane leg swings, standing frontal plane leg swings, body weight squats, and hip thrusts. First, three progressively heavier specific warm-up sets were performed (~60, 70 and 80% of predicted 3 RM), for the front squat, followed by two to three sets of 3 RM testing sets. During the front squat, subjects' feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. Subjects descended until the tops of the

thigh were parallel with the floor (Pierce, 1997). After 10 minutes of rest, subjects performed three progressively heavier specific warm-up sets for the barbell hip thrust. In accordance with Contreras et al. (2011), the barbell hip thrust was performed by having subjects' upper backs on a bench. Subjects' feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. The barbell was padded with a thick bar pad and placed over the subjects' hips. The subjects were instructed to thrust the bar upwards while maintaining a neutral spine and pelvis.

Subjects performed an isometric mid-thigh pull while standing on a force plate (AMTI Accupower, Watertown, MA, USA) within a squat rack. Each subject held onto an adjustable bar using an alternate grip (power grip) that was locked at a height situated halfway between (mid-thigh position) each subject's knee (top of the patella) and top of the thigh (inguinal crease). On the command "go", the subjects were instructed to pull the fixed bar "hard and fast" and maintain maximal effort for five seconds with the intention of generating maximum vertical ground reaction force. Peak vertical ground reaction force was recorded from two trials separated by three minutes of rest. The highest peak force from both trials was used for analysis.

Subjects were matched according to total strength and then randomly allocated to one of two training groups (front squat or hip thrust) via a coin flip. Statistical analysis (t-test) was carried out to ensure that there were no statistically significant between group differences ($p < 0.05$) in the measured baseline variables (Table 9.1). For lower body, one group performed front squats only, while the other group performed hip thrusts only. The repetition scheme utilized for the front squat and hip thrust can be observed in Table 9.2. In addition to lower body training, both groups performed upper body and core exercises, consisting of: four sets of incline press or standing military press; four sets of bent over rows, bench pull, or seated rows; and four sets of core exercises for the abdominals/lower back. Each week, on two separate days

spaced at least 72 hours apart, the front squat group performed four sets of front squats and the hip thrust group performed four sets of hip thrusts in a periodized fashion (Table 9.2). A standardized 10-minute dynamic warm-up followed by three progressively heavier specific warm-up sets was performed prior to each session. Three-minute rest periods in between sets were used throughout the duration of the training. During week one, 60% 3 RM loads were utilized. Loads were increased gradually each week, assuming the subject completed all repetitions with proper form.

Table 9.1. Comparison of baseline characteristics of the squat and hip thrust groups.

	Hip Thrust	Squat	p-value
Age (years)	15.4 ± 1.16	15.4 ± 0.74	0.98
Height (cm)	178 ± 5.02	181 ± 5.51	0.19
Body mass (kg)	78.3 ± 12.4	81.1 ± 12.3	0.58
Vertical jump (cm)	56.3 ± 8.4	52.2 ± 8.40	0.25
Horizontal jump (m)	2.33 ± 0.20	2.28 ± 0.24	0.61
10-meter sprint (s)	1.76 ± 0.07	1.79 ± 0.08	0.24
20-meter sprint (s)	3.13 ± 0.13	3.16 ± 0.14	0.49
Hip thrust (kg)	115 ± 23.5	111. ± 20.9	0.63
Front squat (kg)	77.5 ± 12.3	75.0 ± 10.4	0.59
Isometric mid-thigh pull (N)	2510 ± 394	2650 ± 244	0.38
Isometric mid-thigh pull (normalized) (N/kg)	32.2 ± 4.17	33.0 ± 3.25	0.72

Table 9.2. Sets and repetition schemes utilized for the squat and hip thrust.

Week	Sets	Repetitions	Load
1	4	12	60% 3RM
2	4	10	70% 3RM
3	4	10	75% 3RM
4	4	8	80% 3RM
5	4	8	85% 3RM
6	4	6	90% 3RM

Training records were kept in order to analyze loading progressions. During the week following the six weeks of training, post-testing was conducted in the same fashion as the pre-testing. Subjects were instructed to maintain their current diet and to abstain from performing any additional resistance training.

All data were reduced and entered into Stata (StataCorp, College Station, TX), wherein Shapiro-Wilk tests were performed to ensure normality. For parametric data,

effect sizes (ES) were calculated using Cohen's d (between group: $d = \frac{M_1 - M_2}{S_{pooled}}$;

within group: $d = \frac{M_d}{s_d}$, where s_d is the standard deviation of differences), which was

defined as small, medium, and large for 0.20, 0.50, and 0.80, respectively (Cohen, 1988). The within-group Cohen's d better represents changes due to the intervention, as

it utilizes within-subject differences rather than between-subject differences. For non-parametric data, ES were reported in terms of Pearson's r ($r = \frac{z}{\sqrt{n}}$, where z is the z -score from a Wilcoxon signed-rank or rank-sum test, for within- and between-subject comparisons, respectively), which was defined as small, medium, and large for 0.10, 0.30, and 0.50, respectively (Cohen, 1988). Ninety-five percent (95%) confidence limits (95% CL) of ES were calculated for magnitude-based inferences (Hopkins, Marshall, Batterham, & Hanin, 2009).

9.3 Results

Of the 29 athletes recruited for this experiment, a total of 24 athletes completed the training protocol, as three athletes were removed due to non-adherence and two athletes were removed due to injury. Thirteen subjects successfully adhered to the hip thrust protocol and 11 subjects successful adhered to the squat protocol for all six weeks.

Within the hip thrust group, a number of statistically significant clearly beneficial effects were observed, including 20 m horizontal sprint time, which decreased by 1.70% ($d = 1.14$ (0.54, 1.75)); hip thrust strength, which increased by 30.0% ($d = 2.20$ (1.60, 2.81)); front squat strength, which increased by 6.63% ($d = 0.64$ (0.04, 1.25)); and both the isometric and normalized isometric mid-thigh pulls, which increased by 9.22% ($d = 1.11$ (0.51, 1.72)) and 7.06% ($d = 0.83$ (0.23, 1.44)), respectively. Changes in vertical jump ($\Delta = +3.30\%$; $d = 0.43$ (−0.18, 1.03)), horizontal jump ($\Delta = +2.33\%$; $d = 0.51$ (−0.09, 1.12)), and 10 m sprint times ($\Delta = -1.06\%$; $d = 0.55$ (−0.06, 1.15)), although not statistically significant, are clearly beneficial (Figure 9.1, Table 9.3).

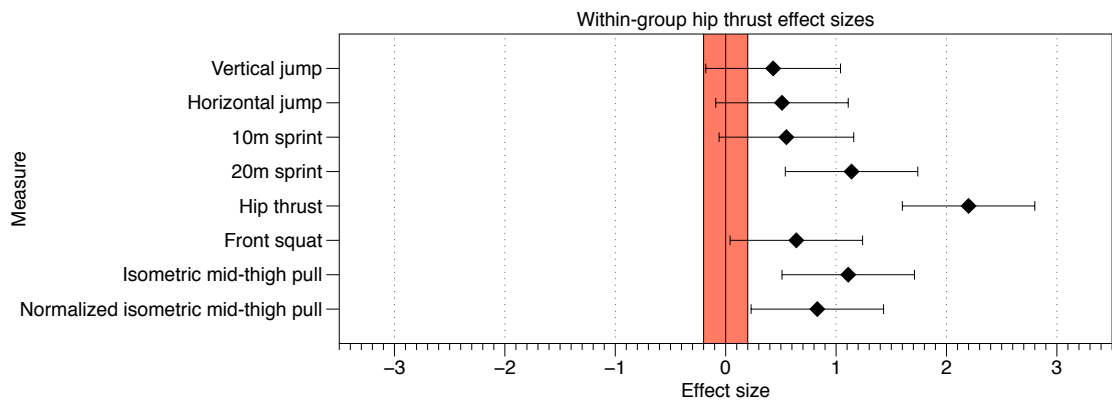


Figure 9.1. Within-group effect sizes (\pm 95% CL) following six weeks of hip thrusting.

Within the front squat group, a number of statistically significant clearly beneficial effects were observed, including vertical jump height, which increased by 6.81% ($d = 1.11$ (0.44, 1.79)), hip thrust strength, which increased by 17.4% ($d = 1.59$ (0.92, 2.26)), and front squat strength, which increased by 11.4% ($d = 1.66$ (0.99, 2.33)). Although possibly due to chance, clearly beneficial effects were observed for horizontal jump ($\Delta = +1.69\%$; $r = 0.29$ (-0.38, 0.76)) and isometric ($\Delta = +1.52\%$; $r = 0.23$ (-0.43, 0.73)) and normalized isometric ($\Delta = +1.56\%$; $r = 0.21$ (-0.45, 0.72)) mid-thigh pulls. Trivial or unclear effects were observed in both 10- ($\Delta = +0.10\%$; $d = -0.02$ (-0.69, 0.65)) and 20 m ($\Delta = -0.67\%$; $d = 0.19$ (-0.48, 0.87)) sprint times (Figure 9.2, Table 9.3).

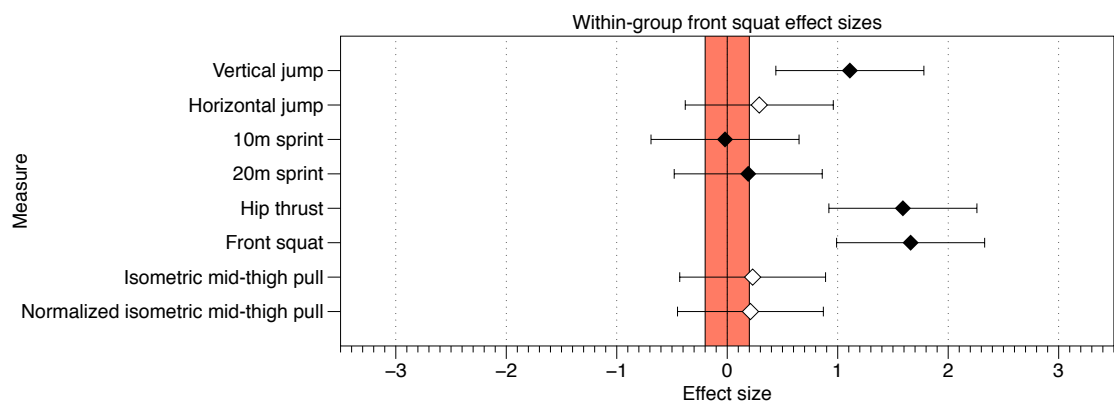


Figure 9.2. Within-group effect sizes (\pm 95% CL) following six weeks of front squatting. Black diamond = Cohen's d , open diamond = Pearson's r .

The hip thrust led to statistically significant ($p < 0.05$) clearly beneficial effects in hip thrust strength ($d = 1.35$ (0.44, 2.23)) and normalized isometric ($r = 0.58$ (0.23, 0.80)) and isometric mid-thigh pull ($r = 0.76$ (0.51, 0.89)). That said, other measures were clearly beneficial, but it cannot be said that these differences were not due to chance. The hip thrust had clearly beneficial effects when compared to the front squat, which may have been due to chance alone (a positive effect-size favors the hip thrust), for 10 m sprint ($d = 0.32$ (−0.50, 1.12)) and 20 m sprint ($d = 0.39$ (−0.42, 1.20)). A trivial or unclear effect was found for the hip thrusts effect on the horizontal jump ($d = 0.15$ (−0.66, 0.95)). The front squat had clearly beneficial effects when compared to the hip thrust on vertical jump height ($d = -0.47$ (−1.28, 0.35)) and front squat strength ($d = -0.55$ (−1.36, 0.27)) (Figure 9.3, Table 9.3).

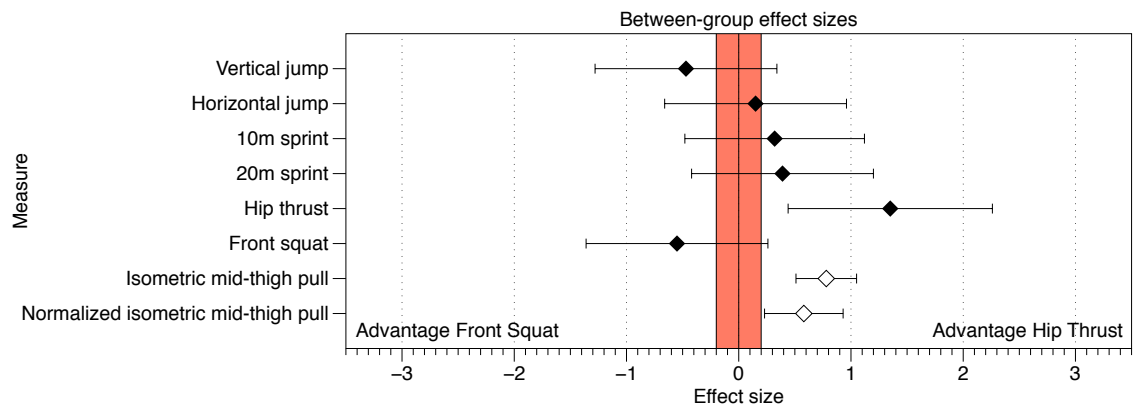


Figure 9.3. Between-group effect sizes (\pm 95% CL) of performance measures. Black diamond = Cohen's d , open diamond = Pearson's r .

Table 9.3. Pre- and post- measures, differences, and percentage change of all performance measures.

	Hip Thrust				Front Squat		
	Pre	Post	Δ (abs)	Δ (%)	Pre	Post	Δ (abs)
Body mass (kg)	78.3 \pm 12.5	79.8 \pm 12.7	+1.49 \pm 1.38	+1.87	81.2 \pm 12.4	81.7 \pm 12.6	+0.55 \pm 1.69
Vertical jump (cm)	56.3 \pm 8.44	58.2 \pm 7.82	+1.92 \pm 4.48	+3.30	52.3 \pm 8.40	56.1 \pm 8.22	+3.82 \pm 3.43
Horizontal jump (m)	2.33 \pm 0.20	2.38 \pm 0.22	+0.06 \pm 0.11	+2.33	2.28 \pm 0.24	2.32 \pm 0.28	+0.04 \pm 0.15
10-meter sprint (sec)	1.76 \pm 0.07	1.74 \pm 0.08	-0.02 \pm 0.03	-1.06	1.79 \pm 0.08	1.80 \pm 0.11	+0.00 \pm 0.09
20-meter sprint (sec)	3.13 \pm 0.13	3.07 \pm 0.14	-0.05 \pm 0.05	-1.70	3.16 \pm 0.14	3.14 \pm 0.16	-0.02 \pm 0.11
Hip thrust (kg)	116 \pm 23.5	165 \pm 33.07	+49.5 \pm 22.5	+30.0	111 \pm 21.0	135 \pm 11.2	+23.5 \pm 14.8
Front squat (kg)	77.6 \pm 12.4	83.0 \pm 13.77	+5.50 \pm 8.53	+6.63	75.0 \pm 10.5	84.6 \pm 10.0	+9.64 \pm 4.80
Isometric mid-thigh pull (N)	2550 \pm 419	2820 \pm 504.21	+261 \pm 258	+9.22	2680 \pm 258	2730 \pm 213	+51.0 \pm 211
Normalized isometric mid-thigh pull (N/kg)	32.8 \pm 4.39	35.4 \pm 4.12	+2.52 \pm 3.30	+7.06	33.4 \pm 3.37	34.1 \pm 4.98	+0.66 \pm 2.35

9.4 Discussion

The purpose of this study was to examine and compare the effects of a six-week squat or hip thrust program on performance measures in male adolescent athletes. Hip thrust within-group analyses revealed clearly beneficial effects for all outcomes. The very large effect size noted for hip thrust strength changes (2.20) is no surprise and is in line with the principle of specificity. Clearly beneficial effects for the hip thrust group to improve front squat strength were noted (0.64). Because the hip thrust has been shown to elicit similar quadriceps as compared to and greater hip extensor EMG amplitude than the squat, these results are intuitive (Contreras et al., 2015a). The decreases in 10 (ES = 0.55) and 20 m (ES = 1.14) sprint times are in line with the force vector hypothesis, as the hip thrust utilizes an anteroposterior or horizontal force vector, and sprint performance is dependant upon horizontal force output (Morin et al., 2011). Clearly beneficial effects in isometric mid-thigh pull (ES = 1.11; Normalized ES = 0.83) were observed as hypothesized and are likely due to the range of motion-specific adaptations of end-range hip extension, which is required during the isometric mid-thigh pull, in addition to the high EMG amplitudes of the hip and knee extensors during

the hip thrust (Contreras et al., 2015a). Lastly, clearly beneficial effects in vertical (0.43) and horizontal (0.51) jump measures were observed as predicted. These outcomes are likely due to the hip thrust's ability to work the hip and knee extensors (Contreras et al., 2015a). Additionally, large horizontal impulses are needed for horizontal jump distance (Wu et al., 2003), so the horizontal force vector employed in the hip thrust may be beneficial for improving this force, and thus, impulse production.

Numerous within-group effects were observed in the front squat group. As per our hypotheses, increases in both front squat (1.66) and hip thrust (1.59) 3 RM were observed. These increases are likely due to the front squat's hip and knee extensor moment requisites (Gullett et al., 2009), which require activation of the hip and knee extensors (Contreras et al., 2015b), and as per previous research by our group, both the squat and hip thrust utilize the hip and knee extensors to a significant degree (Contreras et al., 2015a). In addition, clearly beneficial effects were observed for both horizontal (0.29) and vertical (1.11) jumps. The front squat's vertical force vector likely helps generate vertical force during jumping, thus increasing vertical impulse, which is a key factor for both horizontal (Wu et al., 2003) and vertical (Adamson & Whitney, 1971; Winter, 2005) jumps. Improvements in both isometric (0.23) and normalized isometric (0.21) mid-thigh pulls were also observed. Again, these adaptations may be due to the vertical force vectors of both the front squat and isometric mid-thigh pulls. It is surprising, however, that the front squat only elicited unclear or trivial effects in 10 (-0.02) and 20 m (0.19) sprint performance, as previous research has shown the squat to be an effective intervention for increasing speed (Seitz et al., 2014).

The primary purpose of this investigation was to compare the two interventions, the front squat and barbell hip thrust, on the aforementioned performance outcomes. Clearly beneficial effects for the hip thrust were noted for 10 (0.32) and 20 m (0.39) sprint times, which provides further support for the force vector theory. The hip thrust

was also clearly and statistically ($p < 0.05$) beneficial in increasing hip thrust 3 RM strength (1.35) and isometric (0.76) and normalized isometric (0.58) mid-thigh pulls. While the former was to be expected, as per the principle of specificity, the latter result was unexpected, as the isometric mid-thigh pull utilizes a vertical force vector. This may have to do with the end-range hip extension moment requisites of the isometric mid-thigh pull, which the hip thrust may be more effective in improving. As per our hypotheses, the front squat was clearly beneficial for improving vertical jump (-0.47) and front squat 3 RM strength (-0.55) over the hip thrust, which also supports the force vector theory. Lastly, as per our hypothesis, no clear effect was observed for horizontal jump performance (0.15). This may be because both horizontal and vertical components are important for the horizontal jump (Wu et al., 2003).

To the authors' knowledge, only one other study has demonstrated transfer from one resisted hip extension exercise to another. Speirs, Bennett, Finn, and Turner (2015) investigated the transfer from unilateral (Bulgarian split squats) to bilateral (back squats) hip extension exercises, and vice versa, in addition to their effects on performance. Both exercises were found to have carryover and improve performance. The observed effects in this study were quite fascinating in that each group gained about half that of their exercise-specific counterpart. In other words, for front squat 3 RM strength, the front squat group increased by 11.4% and the hip thrust group increased 6.63%. This effect was also noticed for hip thrust 3RM strength ($+30.0\%$ (hip thrust group) versus 17.4% (front squat group)).

Absolute hip thrust 3 RM strength and changes in hip thrust 3 RM were much greater than the front squat. The front squat group increased their hip thrust 3 RM by 23.5 ± 14.7 kg ($111 \pm 20.9 - 134 \pm 11.2$ kg), while their front squat 3 RM increased by 9.64 ± 5.80 kg ($75.0 \pm 10.4 - 84.6 \pm 10.0$ kg). The differences in the hip thrust group were, of course, even more pronounced, in that their front squat 3 RM increased by 5.50

± 8.53 kg ($77.6 \pm 12.3 - 83.1 \pm 13.7$ kg), while their hip thrust 3 RM increased by 49.5 ± 22.4 kg ($115 \pm 23.5 - 165 \pm 33.0$ kg). These differences are likely due to the nature of the hip thrust exercise, in that there is more stability and decreased coordination requirements. However, a full kinetic analysis of the hip thrust is needed for further insight.

The front squat's ability to increase vertical jump height is quite intuitive, as both the squat and vertical jump utilize the same force vector direction (vertical). Additionally, the utilization of the quadriceps in both the front squat and vertical jump (Gullett et al., 2009; Mackala, Stodolka, Siemienski, & Coh, 2013a; Yavuz et al., 2015) demonstrate a possible underlying mechanism for beneficial vertical jump adaptations (Bloomquist et al., 2013). Lastly, a qualitative analysis of both movements reveals that they are similar in nature. On the other hand, the effects on horizontal jump length are rather surprising, as it was hypothesized that squats and hip thrusts would lead to similar improvements in this test due to the large vertical and horizontal force and impulse requirements of the task (Mackala, Stodolka, Siemienski, & Coh, 2013b; Wu et al., 2003). However, despite clear strength gains in vertically- and horizontally-oriented lower body exercises, neither group saw statistically significant or clearly beneficial improvements in horizontal jump performance.

It is surprising that, although squats have been shown to improve sprint performance (Seitz et al., 2014), no clear effects were observed in the front squat group for sprint performance. It cannot be said whether this is due to short duration of training (six weeks) as weight training has previously been shown to improve 10 m sprint times in the same six-week period (Lockie et al., 2012), and because a nonsignificant, clearly beneficial effect was noted in the hip thrust group. While it is surprising that the front squat did not decrease 20 m times, the effects of the hip thrust are quite intuitive, as horizontal force production is a key component in sprint

performance (Brughelli et al., 2011a; Buchheit et al., 2014; Morin et al., 2011), and the hip thrust is a horizontal force-dominated movement. These findings are in line with what Randell et al. (2010) proposed, in that horizontal-dominated movements have better carryover to horizontal-dominated activities, while vertical-dominated movements have better transference to vertical-dominated activities. On a musculoskeletal level, this may be due to the hip thrust's remarkable ability to recruit the hip extensor musculature (Contreras et al., 2015a). Furthermore, the hip thrust has a hip extension moment requisite throughout the entire range of motion, including end-range hip extension, whereas the squat does not.

Hip thrust training resulted in greater improvements in the isometric mid-thigh pull, as compared to squat training, even though the pull involved a vertical force vector. It is proposed that this is due to the hip extension moment-angle curves of the squat versus that of the hip thrust, in that the hip thrust likely has a greater hip extension moment requisite at the angle at which the isometric mid-thigh pull is performed, but these joint-specific kinetic hypotheses require further investigation.

There are a number of limitations that must be borne in mind when interpreting the results from this study. Adolescent males have changing hormone levels and a large number of life stressors (Arnett, 1999; Sizonenko, 1978). Therefore, these results cannot be extrapolated to other populations, such as female or adult populations. Second, the short, six-week duration (12 total sessions) of this study may not have been enough time to elicit adequate, observable results. This short time span may not be adequate for a squat program, as it requires more coordination than the hip thrust and is easier to learn since it requires less stability. Third, although front squats were only performed to parallel, deeper squats tend to elicit greater adaptations (Bloomquist et al., 2013). This study also dichotomized exercise selection, and it is very likely that a combined group would have the "best of both worlds," or the benefits from both

horizontal and vertical force vector training. The sprinting measured during this trial was of short distance (10 and 20 m), which is the early phase of acceleration. It is possible that with longer distances, different observations may have been made. For example, one group may have increased their top speed but not acceleration, thus leading to lower sprint times at 100 m but not 20 m.

Future research should duplicate these methods in other populations, such as females, adults, and athletes from various sports. Further, finding a proper protocol for improving transference is imperative, as, for example, light, explosive hip thrusts may be better for improving power production, but heavy hip thrusts may be better for horizontal force production. The dichotomization of exercise selection in this study must be eliminated from future research, as combining exercises tends to elicit greater adaptations than one exercise (Fonseca et al., 2014). Determining the transfer of these movements to other movements, such as the transfer of the squat or hip thrust to the deadlift would be helpful for program design purposes. As previously noted, a joint kinetic analysis of the hip thrust to compare to existing analyses on the squat is needed, as this may reveal biomechanical mechanisms for adaptation. Lastly, the hip thrust should be compared to different squat variations, such as the back squat.

9.5 Practical Applications

In line with previous literature, specificity is immensely important for improving the strength of a lift. This indicates that athletes that participate in sports like basketball and volleyball, which are predicated on vertical jump, may benefit more from the front squat rather than the hip thrust. However, in sports such as rugby and American football, it may be more beneficial for athletes to perform the hip thrust, due to its carryover to acceleration. Because the hip thrust does seem to increase front squat performance, it is possible that the hip thrust may be a viable option to perform during

times of injury in order to maintain or increase front squat strength. The force vector principle appears to hold true, in that vertical-based movements (front squat) appear to better transfer to vertical-based activities (vertical jump), and horizontal-based movements (hip thrust) appear to better transfer to horizontal-based activities (20 m sprint). The hip thrust's carryover to the isometric mid-thigh pull is indicative that the hip thrust may have carryover to deadlift lockout, even though the positions are slightly different. Lastly, it is likely best to perform a combination of movements rather than just one; it is recommended that athletes incorporate both the squat and hip thrust for complementary improvements in performance.

***RELIABILITY OF THE MAXIMUM HORIZONTAL PUSH FORCE
TEST***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
Craig Harrison, Timothy Wilson, John Cronin**

**Journal of Strength and Conditioning Research
In Review (Appendix 4i)**

10.0 Prelude

Given one of the contentions of this thesis is that the hip thrust provides superior horizontal force outputs, it would seem prudent to be able to monitor and measure this variable. In sports science research, there is currently no standard test used by researchers to measure athletes' maximum horizontal pushing force. Since horizontal force is important for both forceful and powerful sporting actions, it is important to have a reliable test available to measure it. A novel test has been proposed using a force plate that effectively measures the maximum pushing force an athlete can exert into a wall. If this test is shown to be reliable, it could be used in Chapter 11 to compare the effects of different protocols on maximum horizontal pushing force. This chapter will seek to quantify the reliability of this novel test.

10.1 Introduction

Pushing and horizontal force production is a large component in many sports including rugby (especially during scrummaging, moving through tackles, etc.), American football (especially linemen), MMA, grappling (especially freestyle, Greco Roman, and sumo wrestling), lacrosse (especially during defense), bobsled, strongman (especially during sled pushing), and shotput (or stoneput in the Highland Games). In addition to the aforementioned sports, there is a large body of literature supporting the notion that horizontal force production is more important than vertical force production for faster sprinting speeds and acceleration (Belli et al., 2002; Brughelli et al., 2011a; Buchheit et al., 2014; Funato, Yanagiya, & Fukunaga, 2001; Girard, Brocherie, Morin, Degache, & Millet, 2015; Hunter et al., 2005; Ito, Fukuda, & Kijima, 2008; Kawamori, Nosaka, & Newton, 2013; Kugler & Janshen, 2010; Kuitunen, Komi, & Kyrolainen, 2002; Kyrolainen et al., 2005; Kyröläinen, Komi, & Belli, 1999; Mangine et al., 2013; Mero,

1988; Morin et al., 2012; Morin et al., 2011; Munro, Miller, & Fuglevand, 1987; Nummela, Rusko, & Mero, 1994; Rabita et al., 2015; Randell, 2011). Of relevance, research by Martinez-Valencia, Gonzalez-Rave, Santos-Garcia, Alcaraz Ramon, and Navarro-Valdivielso (2014) examined correlations between half squat strength, resisted sprint strength, and 20 m sprinting velocity. No correlations were found between half squat strength and sprinting ability, but strong correlations were found between maximum loads in sled towing sprints and 20 m sprint times, suggesting that pushing forward is more highly related to acceleration than pushing upward.

Despite the strong body of literature on the importance of horizontal force production for sprint performance, Morin et al. (2012) found that theoretical maximal horizontal force production may not be a strong predictor of maximal speed, acceleration, or 100 m sprint times. Rather, it was found that theoretical maximal horizontal velocity may be a better predictor. These theoretical values were determined via velocity versus relative horizontal force linear regressions equations, where the maximal values for velocity and horizontal force were assumed to be the values where horizontal force equals zero and where velocity equals zero, respectively. In other words, the regression equations were extrapolated to the x and y intercepts, which were velocity and horizontal force, respectively. These findings were, of course, theoretical, and no test has yet been described to test an athlete's maximal horizontal force production. Many researchers have speculated about, or stressed the need to, discover the best methods for improving horizontal force (Beardsley & Contreras, 2014; Contreras et al., 2011; Contreras et al., 2013; de Lacey et al., 2014),

Isometric strength has been shown to be highly correlated with dynamic performance (Juneja, Verma, & Khanna, 2010). Once a method is found to reliably assess maximum horizontal force production, studies can be carried out to determine the correlations between maximum horizontal force, acceleration, maximum speed, and

other performance measures in different populations. The force plate, a ubiquitous measurement tool, is commonly used to measure vertical ground reaction forces during dynamic exercises such as vertical jumps (Dias et al., 2011; Harman, Rosenstein, Frykman, & Rosenstein, 1990), back squats (Aspe & Swinton, 2014; Wallace et al., 2006), and power cleans (Comfort, Allen, & Graham-Smith, 2011a; Souza, Shimada, & Koontz, 2002), in addition to isometric exercise such as mid-thigh pulls (Beckham et al., 2013; Kawamori et al., 2006). It is also used to commonly measure horizontal ground reaction forces during dynamic exercises such as sprinting and bounding (Belli et al., 2002; Brughelli et al., 2011a; Buchheit et al., 2014; Funato et al., 2001; Girard et al., 2015; Hunter et al., 2005; Ito et al., 2008; Kawamori et al., 2013; Kugler & Janshen, 2010; Kuitunen et al., 2002; Kyrolainen et al., 2005; Kyröläinen et al., 1999; Maigne et al., 2013; Mero, 1988; Mero & Komi, 1994; Morin et al., 2012; Morin et al., 2011; Munro et al., 1987; Nummela et al., 1994; Rabita et al., 2015; Randell, 2011). However, previously, it has not been commonly used to measure horizontal forces during isometric exercises. Given this brief treatise of the literature, the rationale for this chapter was twofold: first, to describe a novel method to measure maximal isometric horizontal pushing force; and second, to quantify the reliability of the maximum horizontal push test (MHPT).

10.2 Methods

In order to quantify the reliability of the MHPT, subjects were asked to perform the exercise on three separate occasions separated by at least seven days. Thereafter, standard reliability statistics were used to quantify the test-retest reliability of this novel test.

Nine male subjects (age = 15.2 ± 0.4 years; mass = 63.7 ± 6.73 kg; height = 173 ± 5.75 cm) were recruited from a student population in order to determine the reliability of the horizontal push test. Subjects were recruited from an athlete development program that focused on the movement competency of youth athletes each morning, and all subjects completed a PAR-Q and Informed Consent and Assent before undertaking the assessments. Any participant who answered “yes” to any question on the PAR-Q were excluded. All methods utilized in this study were approved by the Auckland University of Technology Ethics Committee.

Subjects were instructed to participate on three separate testing occasions, with at least seven days in between assessments. A tri-axial force plate (Advanced Mechanical Technology Inc. Acupower, Watertown, MA) was used for data collection (400 Hz) and was positioned on a rubber surface in order to increase static friction to prevent the force plate from slipping during the test. Additionally, three strips of grip tape (Camco Mfg., Greensboro, NC) were placed across the force plate to increase static friction between the subject’s foot and the force plate as to prevent slipping (Figure 10.1). The distance from the force plate to the wall was positioned such that when the subjects’ arms were straightened and parallel with the ground and the torso was at a 45° angle with the ground, the rear foot was in contact with the middle of the force plate. Subjects were instructed to push, using the dominant leg, as hard as possible into the wall while keeping the torso at 45° and the arms straight and parallel with the ground (Figure 10.1). It was found that during the test, the subjects’ position did indeed change slightly, but cueing for the subjects to remain static prevented excessive movement. Plantar flexion was allowed. The horizontal push test was performed three times for three seconds, each separated by three minutes of rest. Subjects were instructed to push “as hard as they can” against the wall, and were also verbally encouraged during the trials. The peak horizontal forces from these three tests were

averaged to represent that day's measurements, the averaged data then used for statistical analysis.



Figure 10.1. Form of the maximum horizontal push test. The body is 45° with the ground and arms are extended and parallel with the ground. N.B. the grip tape on the force plate to increase static friction.

Means and standard deviations were used as measures of centrality and spread of data. To quantify the reliability of the MHPT two measures were used: one, coefficient of variation (CV) as a measure of the absolute consistency and typical error associated with the measurement; and two, intraclass correlation coefficient (ICC), as a measure of relative consistency in rank order of subjects. Ninety percent confidence limits (90% CL) of the log-transformed dataset were calculated using Microsoft Excel® (Microsoft, Redmond, USA) (Hopkins, 2000).

10.3 Results

The reliability statistics of the MHPT are presented in Table 10.1. As can be observed from Table 10.1, there was an increase in means horizontal peak force from Day 1 to Day 3 (~18%) as represented in the change in the mean. In terms of the CVs there was a decrease in variability (0.6%) between testing occasions, and a slight increase in relative consistency with repeated testing as evidenced by the ICCs.

Table 10.1. Reliability of peak horizontal force for the maximum horizontal push test.

Mean \pm SD (N)			Δ Mean (90% CL) (%)		CV (90% CL) (%)		ICC (90% CL)	
Day 1	Day 2	Day 3	Day 2-1	Day 3-2	Day 2-1	Day 3-2	Day 2-1	Day 3-2
432 \pm 70.2	483 \pm 97	521 \pm 101	10.9 (5.32, 16.7)	8.21 (3.33, 13.3)	6.05 (4.31, 10.6)	5.42 (3.86, 9.44)	0.946 (0.826, 0.984)	0.963 (0.878, 0.989)

10.4 Discussion

This is the first study to describe and examine the reliability of the MHPT, and the MHPT displayed acceptable levels of reliability. The differences in the change of the means are usually attributed to random and systematic change. In this study, the large between test differences in the means can most likely be attributed to systematic change, i.e., a learning effect.

The CV is an important form of typical error, expressed as a percentage of the subjects mean score, and allows comparisons between tests and across testing

occasions. A CV of 10% or less has been chosen arbitrarily by some scientists, but the merits of this value have been the source of conjecture (Atkinson & Nevill, 1998). Nonetheless, the test-retest CVs would seem acceptable given these criteria, random variation of 5-6% expected between testing occasions. With familiarisation, the CV would most likely be reduced.

Walmsley and Amell (1996) suggested that ICCs above 0.75 may be considered reliable and this index should be at least 0.90 for most clinical applications. The ICCs of this study certainly are acceptable in respect to these criteria. The reliability of the MHPT is similar to the reliability of other popular isometric force tests, such as the isometric mid thigh pull (MHPT ICC = 0.96 versus IMTP ICC = 0.97) (Kawamori et al., 2006).

Even though the ICCs and CVs appear acceptable, given the large change in the means, it seems that greater familiarization is needed with this test. It would have been interesting to increase the number of testing occasions to observe if the level of variability plateaued, as this would have given some indication as to the number of familiarisation sessions needed. Conversely, it would have been interesting to determine if better within-session familiarisation would have improved the stability of the measures. Furthermore, given this was a youth population, it could be contended that there may be more variability associated with such a sample and better reliability associated with more mature subjects.

10.5 Practical Applications

Although this test was found to be highly reliable, its validity, sensitivity, and correlations with performance measures must be established. Once these measures have been investigated, however, there could be several practical applications for the use of this test. First, the MHPT could be used as an assessment to determine maximum and relative horizontal pushing capabilities. Athletes that display inferior levels of

horizontal force production could be placed on specialized training programs aimed at increasing horizontal pushing strength. Second, the MHPT could be used for research on post-activation potentiation to help determine methods that acutely improve maximum horizontal pushing force. It is possible that these same methods could acutely improve performance in sport activities such as shotput and/or bobsled. Third, the MHPT could be used to map changes in isometric horizontal force capability and dynamic horizontal force capability. Although isometric strength may be related to dynamic performance, it remains to be determined as to how well the MHPT correlates to common measures of dynamic performance such as vertical jumping, horizontal jumping, acceleration, and maximum velocity sprinting. Correlations do not imply causation, but it does aid in hypothesis generation for future research. Fourth, the MHPT could be used in training studies as a pre- and post-test to help determine which protocols most effectively increase maximum horizontal pushing capacity. The MHPT could potentially be used to assist in discovering the best methods of improving horizontal force. Future research should be undertaken to determine the reliability of the MHPT with different populations, determine the validity and sensitivity of the MHPT, and build upon the MHPT by examining different joint angles that better mimic sport specific actions or left to right side balances in order to determine whether asymmetries exist and if these asymmetries are related to injury.

***EFFECTS OF A SIX-WEEK SQUAT VERSUS HIP THRUST
PROGRAM ON GLUTEUS MAXIMUS THICKNESS AND
HORIZONTAL FORCE PRODUCTION IN MONOZYGOTIC TWINS:
A SINGLE-SUBJECT DESIGN***

**Bret Contreras, Andrew Vigotsky, Brad Schoenfeld, Chris Beardsley,
John Cronin**

**Journal of Strength and Conditioning Research
In Review (Appendix 4k)**

11.0 Prelude

In Chapter 7, it was discovered that performing the hip thrust resulted in greater gluteus maximus activation as compared to the squat. In Chapter 9, it was found that hip thrusts better transfer to a number of variables. However, to date, no research has measured increases in gluteus maximus thickness, cross-sectional area, or volume following a squat or hip thrust intervention. Furthermore, no research currently exists examining changes in horizontal force production following a squat or hip thrust training protocol. If the force vector theory holds true, then the hip thrust might better improve maximum horizontal pushing force in comparison to squats. This chapter will seek to measure the effects of squats versus hip thrusts on gluteus maximus thickness and maximum horizontal pushing force in two identical twins.

11.1 Introduction

The gluteus maximus is the largest superficial muscle in the human body (Wilson, Ferris, Heckler, Maitland, & Taylor, 2005). The massive and unique form of the gluteus maximus elucidates its importance for generating hip extension, external rotation, abduction, and posterior pelvic tilt moments (Blemker & Delp, 2005; Dostal, Soderberg, & Andrews, 1986; Neumann, 2010). These moments of force are important in numerous activities, such as walking, running, sprinting, and climbing (Bartlett et al., 2014), in addition to activities of daily living (Marzke, Longhill, & Rasmussen, 1988).

Gluteus maximus size is important for both strength and aesthetics (Centeno, 2006; Cuenca-Guerra & Lugo-Beltran, 2006; Cuenca-Guerra & Quezada, 2004). A number of studies have utilized ultrasound to measure the size of the gluteus maximus (Fukumoto et al., 2012; Ikezoe, Mori, Nakamura, & Ichihashi, 2011a, 2011b; Taniguchi et al., 2015). However, these studies were not experimental in nature. Currently, there is

a paucity of training studies on gluteus maximus hypertrophy. Sakamaki, Bembien, and Abe (2011) found no increase in gluteus maximus volume following three weeks of twice-daily blood flow restricted walk training. Yasuda et al. (2014) reported a 4.4% increase in gluteus maximus cross-sectional area following a 12-week, low-intensity, blood flow-restricted protocol of knee extensions and leg press. Lastly, Popov et al. (2006) found increases in gluteus maximus volume following an eight-week protocol utilizing a leg press. To date, no hypertrophy studies have been completed investigating the effects of the squat or hip thrust on gluteus maximus size.

With regards to hypertrophy research and training studies, inter-individual genetic variation is an important factor to consider (Bamman, Petrella, Kim, Mayhew, & Cross, 2007; Dennis et al., 2009; Thalacker-Mercer et al., 2013; Timmons, 2011). Hubal et al. (2005) found large inter-individual responses in 585 men and women to resistance training for both increases in strength and hypertrophy, ranging from 0 to +250% and -2 to +59%, respectively. The mechanisms for these differences have also been investigated. Although typically thought to be genetically identical, monozygotic twins exhibit similar, but not identical, genomic sequences. These differences arise from mutations and polymorphisms following the splitting of the embryo (Bruder et al., 2008; Weber-Lehmann et al., 2014). However, monozygotic twins are still very similar, and for the purposes of research, twins are extraordinarily useful in helping to reduce much of the genetic variability (Busjahn & Hur, 2006).

Pushing and horizontal force production is a large component in many sports. Furthermore, there is a large body of literature supporting the notion that horizontal force production is more important than vertical force production for faster sprinting speeds and acceleration (Belli et al., 2002; Brughelli, Cronin, & Chaouachi, 2011b; Buchheit et al., 2014; Funato et al., 2001; Girard et al., 2015; Hunter et al., 2005; Ito et al., 2008; Kawamori et al., 2013; Kugler & Janshen, 2010; Kuitunen et al., 2002;

Kyrolainen et al., 2005; Kyröläinen et al., 1999; Mangine et al., 2013; Mero, 1988; Morin et al., 2012; Morin et al., 2011; Munro et al., 1987; Nummela et al., 1994; Rabita et al., 2015; Randell, 2011). Recent work from our group has developed and demonstrated the reliability of the maximum horizontal push test, in which maximum horizontal ground reaction force is tested (Contreras, Vigotsky, Schoenfeld, Beardsley, & Cronin, In Review). Because the squat and hip thrust utilize different force vectors, the effect of force vector direction on maximum horizontal pushing force will be tested. More specifically, the hip thrust utilizes a horizontal, or anteroposterior, force vector, while the squat utilizes a vertical, or axial, force vector. Force vectors have recently been shown to influence torque-angle curves and electromyographic (EMG) activity (Contreras et al., 2013). It is possible that the hip thrust is better suited for developing hip extension strength at the joint-angles tested in the maximum horizontal pushing test.

Single-subject designs are useful for strength and conditioning and physical rehabilitation research (Kinugasa, Cerin, & Hooper, 2004; Perdices & Tate, 2009). Such a design can be implemented in a number of ways, but for the purposes of this study, an AB design will be implemented and will require multiple baseline measures followed by the introduction of an intervention. In the current study, the use of the AB design was used for the purpose of tracking changes in the maximum horizontal pushing force and gluteus maximus hypertrophy in monozygotic twins after training with the squat or the hip thrust. It is hypothesized that the hip thrust will be superior to the squat in increasing both variables of interest.

11.2 Methods

One pair of monozygotic twins were recruited to test the hypothesis that hip thrusts will result in greater gluteus maximus hypertrophy and maximum horizontal pushing force

gains than the back squat. A single-subject research design was utilized, and the differences between baseline and post-intervention were compared.

One pair of female monozygotic twins ($n = 2$; age = 27 years; body mass 63.6 ± 0.45 kg; height 174.63 ± 0.90 cm) was recruited for this study. At the time of recruitment, the twins must have been healthy and injury free. Both twins signed Physical Activity Readiness Questionnaires (PAR-Q) and Informed Consents before beginning. Subjects were instructed not to perform any additional resistance training outside of this experiment, and each were instructed to adhere to an 1800 kcal diet consisting of 130g protein, 200g carbohydrates, and 50g fat. This study was approved by the Auckland University of Technology Ethics Committee.

Before beginning their six-week training protocol, the twins underwent testing for upper and lower gluteus maximus thickness, maximum horizontal pushing force, and hip thrust and squat 1 RMs. Each method of testing is described in the proceeding paragraphs.

In order to measure gluteus maximus thickness, a Chison Q5 ultrasound unit (Chison Medical Imaging Co., Ltd, Wuxi, China) was used. Both the upper and lower portions of the gluteus maximus were measured on three days prior to and following training, in accordance with the electrode locations used by Contreras et al. (2015a), Contreras et al. (2015b), and Hermens et al. (1999). More specifically, a linear probe was placed on the upper gluteus maximus, two finger's width above the line formed between just under the posterior superior iliac spine and greater trochanter. The lower gluteus maximus was measured just below the same line (Hermens et al., 1999). Thickness was assessed on the longitudinal plane, using B-mode, an 8-MHz transducer, and 70-dB gain (Fukumoto et al., 2012; Ikezoe et al., 2011a, 2011b). Although these methods have been previously validated and have been shown to have a test-retest

intraclass correlation of 0.991 (Ikezoe et al., 2011b), the intrarater reliability for the tester of this study was not calculated.

A tri-axial force plate (Noraxon, Scottsdale, AZ) was used for data collection (2000 Hz) and was positioned on a rubber surface in order to increase static friction coefficients to prevent the force plate from slipping during the test. Additionally, three strips of grip tape (Camco Mfg., Greensboro, NC) were placed across the force plate to increase static friction between the subjects' foot and the force plate as to prevent slipping. The distance from the force plate to the wall was positioned such that when the subjects' arms are straightened and parallel with the ground and the torso is at a 45° angle with the ground, the rear foot is in contact with the middle of the force plate. The subjects were instructed to push, using the dominant leg, as hard as possible into the wall while keeping the torso at 45° and the arms straight and parallel with the ground. It was found that during the test, the subjects' position did indeed change slightly, but cueing for the subjects to remain static prevented excessive movement. The horizontal push test was performed three times for three seconds, each separated by three minutes of rest. The peak horizontal forces from these three tests were averaged together to represent that day's measurements. These methods have been shown to have a 0.95 intraclass correlation coefficient of test-retest reliability.

Subjects first performed a 10-minute lower body dynamic warm-up consisting of two sets of 10 repetitions of the following movements: standing sagittal plane leg swings, standing frontal plane leg swings, body weight squats, and hip thrusts. First, three progressively heavier specific warm-up sets were performed (~60, 70 and 80% predicted 3RM), followed by two to three sets of 1 RM testing sets. The 1 RM protocol was only performed once prior to the commencement of training, as to not fatigue the subjects. Following training, the 1 RM testing protocol was performed on three occasions. During the back squat, subjects' feet were slightly wider than shoulder width

apart, with toes pointed forward or slightly outward. Subjects descended until the tops of the thigh were parallel with the floor (Pierce, 1997). In accordance with Contreras et al. (2011), the barbell hip thrust was performed by having subjects' upper backs on a bench, approximately 38 cm high with a 2 cm pad. Subjects' feet were slightly wider than shoulder width apart, with toes pointed forward or slightly outward. The barbell was padded with a thick bar pad and placed over the subjects' hips.

Both subjects underwent the same daily-undulated periodized training protocol. One subject was to perform the hip thrust as her only lower body exercise, and the other was to perform the squat as her only lower body exercise. Subjects trained three times per week following the protocol shown in Table 11.1. Additionally, subjects performed two sets of either incline press, bench press, or close grip bench press; two sets of either lat-pulldown, band assisted chin-up, or modified inverted row; and two sets of either hanging leg raise, straight leg sit-up, or ab-mat crunch. Loads used were increased with levels of strength, as to keep the relative loading approximate for all weeks.

Table 11.1. Training protocol.

Day 1			Day 2			Day 3		
Set	Repetitions	Load	Set	Repetitions	Load	Set	Repetitions	Load
1	10	~75%	1	6	~85%	1	15	~65%
2	10	~75%	2	6	~85%	2	15	~65%
3	10	~75%	3	6	~85%	3	AMRAP	~65%
4	AMRAP	~75%	4	6	~85%			
			5	AMRAP	~85%			

The differences between pre- and post-intervention means were compared using: one, visual analysis, which was used to determine changes in level; and two, standard deviation (SD) method, which involved calculating the mean and standard deviation of the baseline phase for each variable. Two standard deviations were then added to the mean baseline value. Two lines were then placed on the graph at mean \pm 2 SD. A significant treatment effect was noted if post training data points were greater

than the two standard deviations above the post training data points (Nourbakhsh & Ottenbacher, 1994).

The two standard deviation band method was not used to quantify changes in the strength measures, as it has been the experience of these researchers that 1RM strength in untrained subjects increases greatly over repeated testing occasions, due primarily repeat testing acts as a training stimulus. Pre-post intervention changes therefore were simply quantified as percent changes.

11.3 Results

The squat exhibited 113% greater approximate time under tension than the hip thrust throughout the entire training protocol (2960 vs. 1390 sec). However, the hip thrust exhibited 135% greater volume load than the squat over the entire training protocol ($5.90 \cdot 10^4$ vs. $2.51 \cdot 10^4$ kg) (Figure 11.1). Interestingly, time under tension multiplied by volume load reveals rather similar figures (squat: $7.5 \cdot 10^7$ kg·s; hip thrust: $8.2 \cdot 10^7$ kg·s). The twin that performed the squat lost 1.4 kilograms during the six-week period (64 to 62.6 kg), but the twin that performed the hip thrust did not change body mass (63.3 kg).

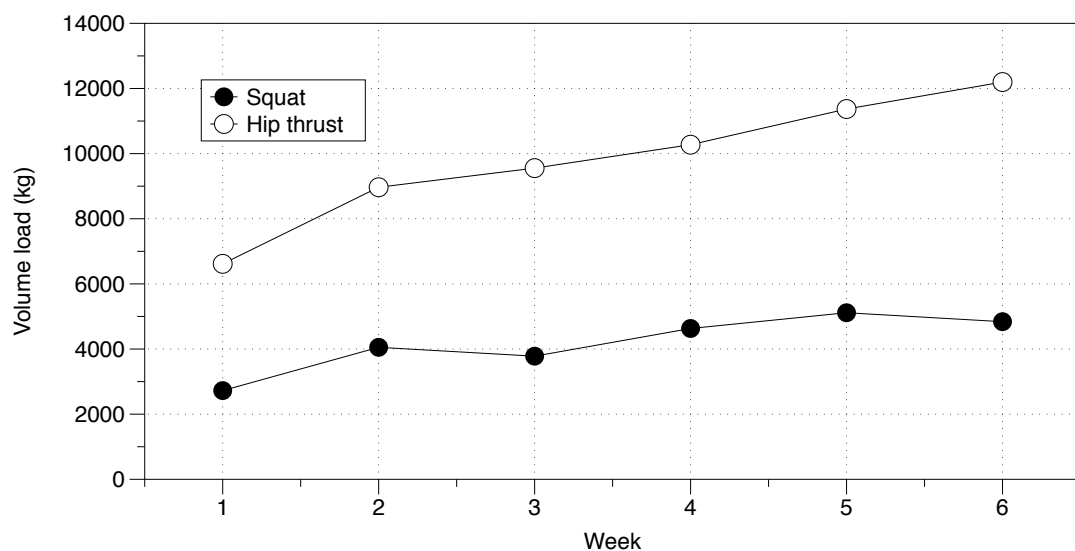


Figure 11.1. Volume load (kg) in the squat and hip thrust across all six weeks.

Changes (~20–23%) in gluteus maximus thickness from the six-week intervention are presented in Table 11.2 and Figure 11.2. In terms of the visual analysis of Figure 11.2 there is a clearly observable change in level between pre and post measures. This is confirmed via the statistical analysis the changes between upper and lower gluteus maximus thickness following both the squat and hip thrust training were greater than two standard deviations above baseline, which means these changes were statistically significant.

Table 11.2. Changes in gluteus maximus thickness (cm).

		Pre	Post	Δ		$\Delta_{\text{AHT-ASQ}}$	
				Absolute	%	Absolute	%
Upper	Squat	2.17	2.62	0.450	20.7	0.066	2.73
	Hip thrust	2.20	2.71	0.516	23.5		
Lower	Squat	2.15	2.59	0.436	20.3	0.064	2.89
	Hip thrust	2.16	2.66	0.500	23.1		

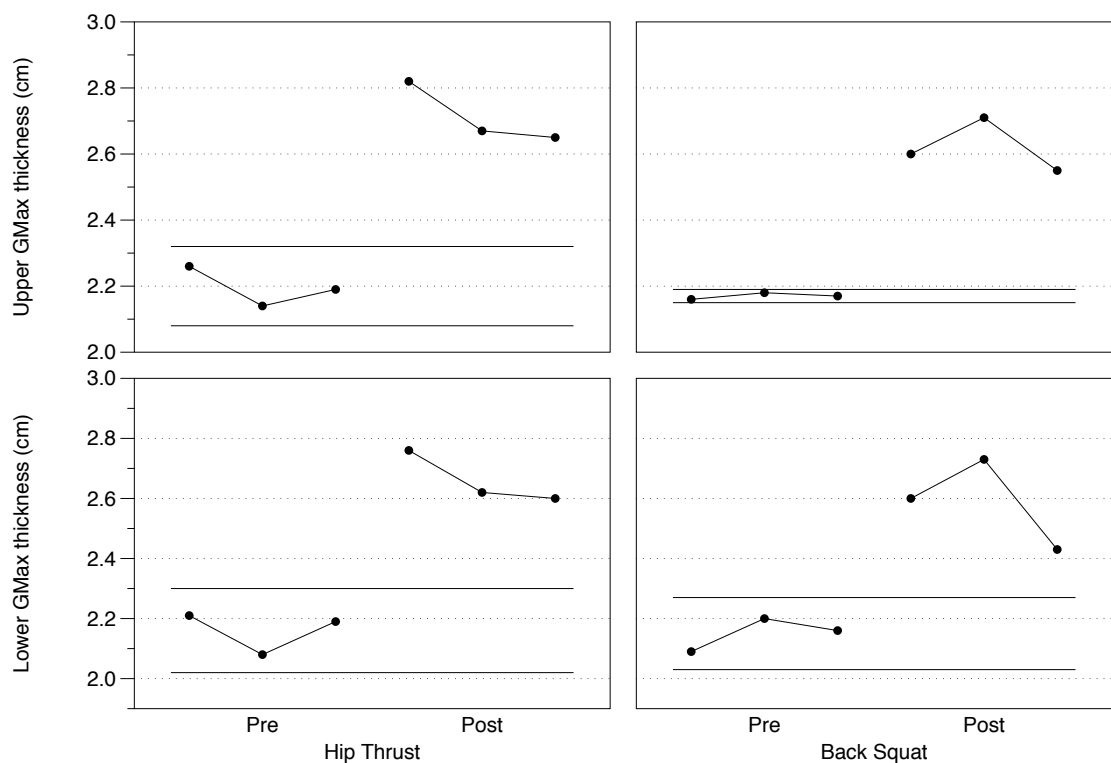


Figure 11.2. Changes in gluteus maximus thickness (cm). GMax = gluteus maximus.

Horizontal lines depict $\pm 2SD$ from baseline mean.

Changes (~20–32%) in maximum horizontal pushing force (MHPT) can be observed in Table 11.3 and Figure 11.3. The visual analysis of Figure 11.3 reveals a clearly observable change in level between pre and post measures for the hip thrust, the squat a little less clear. This is confirmed via the statistical analysis, the changes in force output across all three testing occasions following the hip thrust were greater than two standard deviations above baseline, whereas only two of the post-intervention data points were greater than 2SD for the squat and the changes were less in magnitude.

With regards to the squat and hip thrust 1RM testing, the squat increased squat and hip thrust strength by 63.2% and 15.6%, respectively, and the hip thrust increased squat and hip thrust strength by 42.1% and 65.0%, respectively. The squat outperformed the hip thrust in improving squat strength by 22.8%, and the hip thrust outperformed the squat in improving hip thrust strength by 49.4% (Table 11.3).

Table 11.3. Changes in strength measures.

		Pre	Post	Δ		$\Delta_{\text{AHT-ASQ}}$	
				Absolute	%	Absolute	%
MHPF (N)	Squat	309	370	61.4	19.9	40.6	12.0
	Hip thrust	320	422	102	31.8		
Squat (kg)	Squat	43.1	70.3	27.2	63.2	-9.83	-22.8
	Hip thrust	43.1	61.2	18.1	42.1		
Hip thrust (kg)	Squat	102	118	15.9	15.6	41.6	49.4
	Hip thrust	88.5	146	57.5	65.0		

MHPF = maximum horizontal pushing force

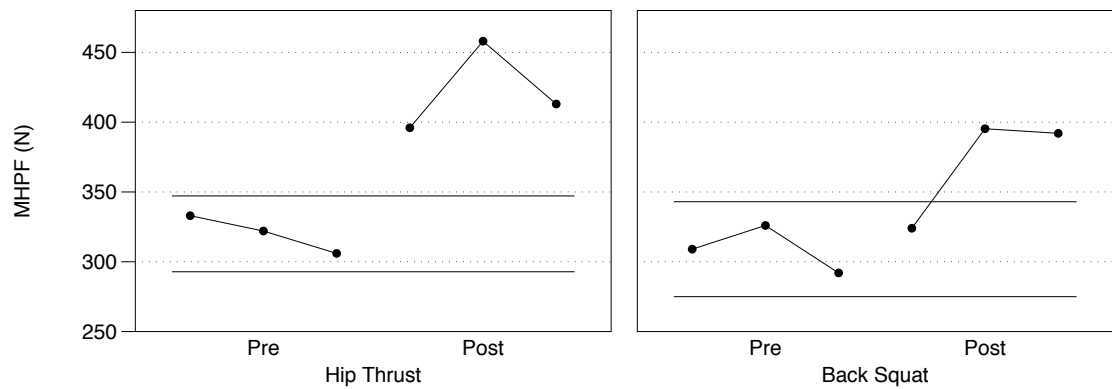


Figure 11.3. Changes in maximum horizontal pushing force (MHPF). Horizontal lines depict $\pm 2SD$ from baseline mean.

11.4 Discussion

All hypotheses regarding gluteus maximus hypertrophy were confirmed, in that both the squat and barbell hip thrust elicited significant increases in upper and lower gluteus maximus thickness. The hypothesis that the hip thrust would lead to greater gluteus maximus hypertrophy was found to be true, in that the hip thrust led to greater percentage increases in upper (2.73%) and lower (2.89%) gluteus maximus thickness. However, it needs to be noted that both exercises produced statistically significant changes to thickness in terms of the 2SD band method, and whether the between exercise percent changes are statistically different is unknown. A greater effect size was noted in the upper gluteus maximus in the squat than the hip thrust (7.72 vs. 6.68); this difference is due to the lower SD in the squat twin. A much greater effect size was found in the lower gluteus maximus for the hip thrust when compared to the squat (6.32 vs. 3.84), which is partly due to the larger pre-post difference, and partly due to the smaller SD in the hip thrust's post measure. In terms of strength gain, all hypotheses were confirmed, except for the back squat being a better training stimulus for increasing maximum horizontal pushing force i.e., the hip thrust training transferred better to the MHPT. It is not surprising that the hip thrust increased hip thrust strength to a greater

degree than the squat (49.4%), and that the squat increased squat strength greater than the hip thrust (22.8%). The hip thrust also led to greater increases in maximum horizontal pushing force than the back squat (12.0%).

This was the first study to investigate the effects of progressive overload resistance training on gluteus maximus hypertrophy. It was found that both the squat and hip thrust elicit remarkable increases in both upper and lower gluteus maximus thickness following a six-week program in persons that have not previously performed progressive overload training protocols. These increases are greater than those previously reported for both the gluteus maximus (Popov et al., 2006; Sakamaki et al., 2011; Yasuda et al., 2014), in addition to other muscles, such as the biceps brachii, which have been shown to have increases in thickness as much as 12.7% in eight weeks (Schoenfeld, Ratamess, et al., 2014). However, Popov et al. (2006) did report a 17% increase in gluteus maximus volume, which is slightly less than the values reported in this study. These superior values may be due to the previously discussed genetic variability, and that these twins are hyper-responders to resistance training. Additionally, both twins were athletic, but had not previously performed resistance training with progressive overload; therefore, they were sensitive to this novel stimulus. These results also contradict the commonly held belief that a muscle does not hypertrophy until six-weeks after beginning a training protocol, as proposed by Sale (1988). In addition, Schuenke et al. (2012) found similar percent increases in cross-sectional area of the vastus lateralis to those reported in this study following a six-week training protocol in untrained women. It could be that ‘super muscles’ – that is, the gluteus maximus and vastus lateralis – have a larger potential for hypertrophy and are more sensitive to training stimulus than smaller muscles (Ward, Eng, Smallwood, & Lieber, 2009). Lastly, the increases in hypertrophy were not necessarily proportional to the differences found in the upper and lower gluteus maximus for each exercise

(Contreras et al., 2015a), suggesting that electromyographic activity may not be a good indicator of hypertrophy. This is logical, as many factors influence electromyographic activity (Dimitrova & Dimitrov, 2003; Enoka & Duchateau, 2015), and that not all mechanisms of hypertrophy require high levels of activation, such as muscle damage (Schoenfeld, 2010a), which appears to be more related to active strain (or relative change in length while active) than stretch (Lieber & Friden, 1993).

The increases in strength for both the squat and hip thrust are not surprising, and align with the principle of specificity. It was found that squat training increases squat strength more than the hip thrust, and that hip thrust training increases hip thrust strength more than the squat. This is not to say, however, that there is not transference between exercises, as both the squat and hip thrust elicited respective increases in hip thrust and squat 1RM strength. In this regard, it appears that the hip thrust has more carryover to the squat (42.1%) than does the squat to the hip thrust (15.6%).

The increase in maximum pushing force elicited by the hip thrust was greater (12%) than that of the squat, which supports the force vector hypothesis, as the hip thrust utilizes a horizontal or anteroposterior force vector, and the squat utilizes a vertical or axial force vector. Further research is warranted in this regard in order to extrapolate these findings to other populations; e.g., athletic or well trained. Furthermore, it needs to be established whether such increases translate to improved functional performance such as acceleration and maximum velocity.

One should interpret the results of this study with caution, as no inter-rater reliability was calculated for the ultrasound, even though previous studies have reported that the methods for measuring gluteus maximus thickness with ultrasound are quite reliable. However, using the multiple baseline testing approach we were able to establish intra-rater reliability (co-efficient of variation = 2.26%). In addition, this study was a single-subject design that utilized monozygotic twins, so these results cannot be

extrapolated to other populations. These twins had unique anatomies, which seemed to be more conducive to hip thrusting than squatting, due to their anthropometry. More specifically, studies have suggested that a greater crural index is more beneficial for squatting (Lovera & Keogh, 2015), but the twins in this study had rather low crural indices (0.89 and 0.94 for the squat and hip thrust twin, respectively). The differences between time under tension and volume load between conditions appears to be mitigated when one combines them (that is, multiplies - global measure of impulse). It is certainly possible that a combined group, or in this case, triplet, would have experienced “the best of both worlds”, or experienced unique effects with combining the squat and hip thrust. Lastly, other muscles involved, such as the biceps femoris and vastus lateralis (Contreras et al., 2015a), were not examined via ultrasound.

11.5 Practical Applications

While this study was just a single-subject design, monozygotic twins were utilized to minimize genetic variability. In this respect, the results are telling, in that the hip thrust performs quite well in comparison to the squat for eliciting gluteus maximus growth, hip thrust strength, and maximum horizontal pushing force. Also, intuitively, squat training better transfers to increasing squat strength as does hip thrust training to hip thrust strength. Importantly, there appears to be transference from the squat to the hip thrust and from the hip thrust to the squat, albeit to a greater extent from the hip thrust to the squat. From these data, it is recommended that those seeking gluteus maximus hypertrophy incorporate the hip thrust as a part of their training protocol. Furthermore, the hip thrust appears to be better for increasing maximum horizontal pushing force, so athletes in sports involving horizontal force production may benefit from incorporating the hip thrust into their training program. Lastly, the hip thrust may be beneficial to maintain squat strength during times of injury.

***SUMMARY, PRACTICAL APPLICATIONS AND FUTURE
RESEARCH DIRECTIONS***

12.1 General Summary

This doctoral thesis by publication was conducted to improve our understanding of the nature of transfer between vertical- and horizontally-loaded hip extension exercises to performance. The underlying objective was to enhance program design for personnel in charge of the training of athletes. This thesis contains a number of intriguing findings, which will be discussed on a chapter-by-chapter basis.

In Chapter 2, through a comprehensive literature review, it was found that the Atlas stone lift and prone weighted bent-leg hip extension likely exhibited the highest levels of peak and mean gluteus maximus EMG activity, respectively, out of the existing published studies to date. It is important to note that both of these exercises have high hip extension moment requisites at end-range hip extension, indicating that just like standard MVIC positions, the gluteus maximus elicits high levels of EMG activity when the hip is fully extended and under high levels of tension.

Chapter 3 served a pinnacle role in this thesis, as it one, introduced the suggested technique to be used in a barbell hip thrust, and two, illustrated that horizontally-loaded hip extension exercises tend to exhibit greater levels of torque and end-range hip extension compared to vertically-loaded hip extension exercises. Since it is thought that the barbell hip thrust will eventually become a commonly used exercise in the preparation of athletes and a commonly examined exercise in the literature, it was important to provide a solid foundation for athletes, coaches, and researchers to work with in terms of exercise form and performance. Furthermore, it was also important to establish a mechanism through which horizontally-loaded hip extension exercises produced such high levels of gluteus maximus activity, which was achieved by combining the findings of Worrell et al. (2001) with Contreras et al. (2015a).

In Chapter 4, it was found that the current gold standard MVIC position commonly used for normalizing gluteus maximus EMG activity, PRONE, significantly outperformed the SQUEEZE position in upper and lower gluteus maximus activation. However, since some subjects achieved greater EMG activation with the SQUEEZE technique compared to the PRONE, it was recommended that both positions be used when conducting MVIC trials for gluteus maximus EMG research.

Chapter 5 showed that barbell squat variations, when using identical relative loading, tend to exhibit markedly similar EMG activity in the gluteus maximus, biceps femoris, and vastus lateralis, at least in relation to the full, parallel, and front squat. Similarly, in Chapter 6, it was found that hip thrust variations, when using identical relative loading, tend to exhibit similar EMG activity in the gluteus maximus, biceps femoris, and vastus lateralis, in relation to the barbell, American, and band hip thrust. For these reasons, it is recommended that lifters, athletes, coaches, and trainers program squat and hip thrust variations that are comfortable and feel ideal for their body types rather than grind away at variations that may not be well-suited for their unique anatomies.

In Chapter 7, it was shown that barbell hip thrusts activate the upper and lower gluteus maximus and biceps femoris to a greater degree (mean upper gluteus maximus ES = 1.55; mean lower gluteus maximus ES = 1.65; mean biceps femoris ES = 1.58) than do back squats. However, vastus lateralis EMG activity was similar between the two exercises. Additionally, in Chapter 8, it was found that squats produced higher levels (mean vastus lateralis ES = -0.15) of total average force, eccentric average force, total impulse, total work, and total average power than hip thrusts, whereas hip thrusts led to the production of higher levels of concentric average (ES = 0.48) force than squats.

In Chapter 9, despite evidence of a clear learning effect existing and despite the absence of a familiarization protocol, the MHPT was still shown to be highly reliable in adolescent males. This means that coaches and researchers can confidently use this test to help determine which exercises, methods, and protocols are best suited for improving maximum horizontal pushing force. In addition, researchers could potentially use the MHPT in attempt to determine post-activation potentiation protocols that acutely increase horizontal pushing force and to determine if correlations exist between maximum horizontal pushing force and other performance measures such as 10 m acceleration, assuming it is shown to have adequate validity and sensitivity.

Chapter 10 led to a number of important findings. First, in accordance with the principle of specificity, front squats increased 3 RM front squat strength and hip thrusts increased 3 RM hip thrust strength. However, it was somewhat surprising to find that front squats increased hip thrust strength around half as much as hip thrusts did, and hip thrusts increased front squat strength around half as much as front squats did. Therefore, a clear transference exists between these two exercises, at least in adolescent males. The hip thrust was found to be superior to the front squat for improving isometric mid-thigh pull strength.

The front squat was better suited for improving vertical jump compared to the hip thrust. However, neither the front squat nor the hip thrust effectively increased horizontal jumping performance. Additionally, although neither the front squat nor the hip thrust effectively increased 10 m acceleration, the hip thrust effectively improved 20 m acceleration times, whereas the front squat did not. In this case, the force vector appeared to play a role in transference from the front squat to the vertical jump and from the hip thrust to acceleration, but strangely, not from the front squat to the isometric mid-thigh pull. The horizontally-loaded hip thrust was better suited for improving isometric mid-thigh pull strength than the front squat, probably due to the

inherent hip extension moment requisites between the two exercises at the precise joint angles associated with the isometric mid-thigh pull test.

In Chapter 11, a single subject design on a pair of identical twins was utilized to show the transfer of squats versus hip thrusts to gluteus maximus hypertrophy. Findings showed that both squats and hip thrusts led to large improvements in upper and lower gluteus maximus muscle thickness. The chapter also examined three measures of strength: the MHPT, 1 RM squat, and 1 RM hip thrust. The hip thrust effectively increased maximum horizontal pushing force, whereas the squat did not. Squats led to large improvements in squat strength and hip thrusts led to large improvements in hip thrust strength. In this particular set of twins, hip thrusts transferred to squats to a greater degree than squats transferred to hip thrusts. In this single subject design, the force vector appeared to play a role in transference from the hip thrust to the MHPT.

12.2 Limitations

Just as in the case with every doctoral thesis, this thesis contains many limitations. In Chapter 2, it was found during a review of the past EMG literature pertaining to gluteus maximus activity in resisted hip extension exercises that not a single comprehensive published study examining the gluteus maximus EMG activity in a variety of popular resisted gluteal exercises exists. Because factors such as MVIC position, electrode site placement, load, effort, tempo, ROM, and amplitude presentation highly influence the data on EMG activity, it is problematic to draw conclusions from comparisons between EMG studies. Moreover, the barbell hip thrust, thanks to this thesis, has now been measured, and its extremely high levels of gluteus maximus activity warrant comparisons with other exercises, including the Atlas stone and prone weighted bent-leg hip extension.

Chapter 3 contained several limitations. First, since the time of the publication of the technique paper, new discoveries pertaining to form have been made. The barbell hip thrust technique paper failed to incorporate any mention about optimal bench height, pelvic tilt, or head and neck position throughout the movement. In addition, for simplicity's sake, straight leg hip extension exercises were used for analysis, though the barbell hip thrust is a bent-leg hip extension exercise with the exerciser rotating about a bench and a floor. Ideally, the barbell hip thrust hip extension moment-angle curve would have been calculated which would have prevented assumptions from being made about its hip extension moment requisites throughout the thesis.

In Chapter 4, only two MVIC tests were compared. Ideally, a handful of positions would have been tested, including a recently published isometric position involving prone hip extension in a hip abducted and externally rotated position (Suehiro et al., 2014). Unfortunately, this study was not published at the time we conducted our study, as we would have incorporated it due to the very impressive levels of gluteus maximus activation it elicited.

Chapter 5 utilized a high bar squat technique during the full and parallel squats. Had low bar full and parallel squats been included, different results may have been determined. Furthermore, only 10 RM loads were tested; different results may have been seen with heavier or lighter loads. Finally, the results of this study pertain to adult females and cannot necessarily be extrapolated to other populations.

In Chapter 6, the band tension was not pre-determined via a force plate, and even if it were, it would have still been difficult to use a legitimate 10 RM load for each subject due to the lack of precise loading possibilities with varying band combinations. Due to the differences in kinetics between barbell and band resistance, it is plausible that different results might have been found had varying loads been tested. In addition,

this study examined adult women and do not automatically apply to other populations such as men, youth, elderly, or elite athletes.

Just as in the cases of Chapters 5 and 6, the results of Chapter 7 pertain to adult females using 10 RM loads and cannot necessary be extrapolated to other populations or different loading schemes.

Chapter 8 also used 10 RM loads and cannot be extrapolated to other loading schemes, and the study examined adult males and cannot be extrapolated to other populations. Furthermore, the study failed to include other important variables of interest, including velocity and rate of force development, and many of the variables examined were not split into concentric and eccentric phases. Finally, it is very likely that the study was underpowered, leading to type II errors.

Chapter 9 failed to incorporate a familiarization protocol, which would have made for more reliable data. However, “statistical significance” was still achieved. Only one torso angle (45°) was examined. Ideally, multiple positions would have been explored.

Only 12 total training sessions over a six-week period were performed by subjects in Chapter 10, which could have lead to the committing of type II errors. Furthermore, the study failed to examine a combined group, which likely would have produced some interesting results. No measurements of maximal velocity sprinting, longer duration runs, triple jumps, or maximum horizontal pushing force were undertaken. The study used adolescent males, and these subjects possess varying hormonal levels, which is an important limitation to note. Finally, the study utilized a specific periodization approach – different results might have been seen with varying combinations of volume, load, effort, frequency, and variations of squats and hip thrusts. Therefore, the findings cannot be extrapolated to other populations or program designs.

Chapter 11 was a single-subject design study that examined two identical twins. Though very intriguing and beneficial for hypothesis generation, it is important to note that the twins could have been good or poor responders to exercise, so similar results will likely not be achieved in all subjects. Furthermore, the twins' anatomy might be more conducive to the squat or the hip thrust, which would favor one exercise over the other, hence why it is important to conduct randomized-controlled trials with sufficient sample sizes to control for individual differences. In addition, a combined group performing both the squat and hip thrust was not possible, as that would have necessitated identical triplets, which were not available when the study was undertaken. Finally, the study failed to measure changes in biceps femoris and vastus lateralis muscle thickness, along with changes in other key muscles.

A general limitation of the thesis is that different percentages of loads between the hip thrust and squat exercises were used. In Chapter 7, 10 RM loads between the hip thrust and squat were 87.4 ± 19.3 kg and 53.2 ± 17.0 kg, respectively, which is 64.3% greater for the hip thrust. In Chapter 8, 10 RM loads between the hip thrust and squat were $114. \pm 35.5$ kg and 98.0 ± 20.4 kg, respectively, which is 16.8% greater for the hip thrust. Finally in Chapter 11, 10 RM loads between the hip thrust and squat were 70.6 kg and 32.3 kg, respectively, which is 118% greater for the hip thrust. Possible differences in loads used across different studies include population and stringency in technique execution. It may be the case that women possess greater hip thrust-to-squat strength ratios than men, but factors such as anthropometry and training experience likely influence this ratio as well.

This thesis found that the force vector theory held true in that vertically-loaded squats transferred better to vertical jumping than horizontally-loaded hip thrusts, whereas horizontally loaded hip thrusts transferred better to acceleration and horizontal

pushing force than vertically-loaded squats. However, the force vector theory did not hold true in the case of the isometric mid-thigh pull, whereby horizontally-loaded hip thrusts transferred better than squats even though the isometric mid-thigh pull is a vertically-loaded test. This is probably due to the fact that squats strengthen the hip and knee extensors in deep positions of flexion, whereas the hip thrust strengthens the hips more so at end-range hip extension. The isometric mid-thigh pull tests strength in moderate levels of hip flexion, which might be too extended of a position to allow for the transfer from squats. Although this thesis provides some evidence that the force vector influences the nature of transfer between exercises and activities, it did not adequately determine the mechanisms responsible for doing so, and it did not do so in a thorough manner. It may be the case that the squat and hip thrust are special in that they allow for heavy loading, high levels of muscle activation in certain muscles, and high levels of certain force-time characteristics, which allows for specific adaptations to take place that are unique to their respective force vectors, and that other exercises won't see the same degree of transfer.

12.3 Practical Applications

There are numerous practical applications associated with this thesis. Chapter 2 determined that the Atlas stone lift and the prone weighted bent-leg hip extension are excellent choices of exercises to highly activate the gluteus maximus. In Chapter 3, it was shown that hip extension exercises with varying force vectors exhibit unique torque-angle curves. These curves can be used to elicit potentially unique acute responses and longitudinal adaptations in terms of muscle damage, metabolic stress, mechanical tension, optimal length, and joint-angle and vector specific strength and power.

Chapter 4 demonstrated that when conducting EMG research on the gluteus maximus, researchers utilizing multiple MVIC positions would record more valid data.

Based on the findings in Chapters 5 and 6, coaches, trainers, athletes, and lifters can confidently employ their preferred variation of squats and/or hip thrust without fearing that their results will suffer if they fail to incorporate other variations. For example, if an individual prefers front squats and American hip thrusts, he or she would likely experience similar results had he or she chosen to perform full squats and band hip thrusts.

The findings from Chapters 7 to 11 are best shown in a chart (Table 12.1). Individuals seeking higher upper and lower gluteus maximus mean and peak EMG activity, mean and peak biceps femoris EMG activity, loading, concentric average force, and transfer to horizontal jump, 10 m and 20 m acceleration, hip thrust strength, isometric mid-thigh pull strength, isometric horizontal pushing strength, and upper and lower gluteus maximus muscle thickness may experience more favorable adaptations by opting for the hip thrust over the squat.

Table 12.1. Comparison of squats and hip thrusts.

	Squat (or Front Squat as Used in the Training Study)	Hip Thrust
Upper Gluteus Maximus Mean EMG Activity (% MVIC)	29.4%	69.5%
Upper Gluteus Maximus Peak EMG Activity (% MVIC)	84.9%	172%
Lower Gluteus Maximus Mean EMG Activity (% MVIC)	45.3%	86.8%
Lower Gluteus Maximus Peak EMG Activity (% MVIC)	130%	216%
Biceps Femoris Mean EMG Activity (% MVIC)	14.3%	40.8%
Biceps Femoris Peak EMG Activity (% MVIC)	37.5%	86.9%
Vastus Lateralis Mean EMG Activity (% MVIC)	110.4%	99.5%
Vastus Lateralis Peak EMG Activity (% MVIC)	244%	216%
Average Force (N)	118	94.5
Total Impulse (N.s)	2520	1570
Total Work (J)	1010	674.0
Total Time (s)	22.1	18.0
Average Power (W)	48.3	43.4
Concentric Force (N)	126	158
Eccentric Force (N)	112	56.5
Bar Displacement (m)	0.66 *	0.37
Transfer to Vertical Jump	↑ 6.81% *	↑ 3.30%
Transfer to Horizontal Jump	↑ 1.69%	↑ 2.33%
Transfer to 10m Acceleration	↑ 0.10%	↓ 1.06%
Transfer to 20m Acceleration	↓ 0.67%	↓ 1.70% *
Transfer to Front Squat Strength	↑ 11.4% *	↑ 6.63% *
Transfer to Hip Thrust Strength	↑ 17.4% *	↑ 30.0% *
Transfer to Isometric Mid-Thigh Pull Strength	↑ 1.52%	↑ 9.22% *
Transfer to Relative Isometric Mid-Thigh Pull Strength	↑ 1.56%	↑ 7.06% *
Transfer to Isometric Maximum Pushing Strength	↑ 19.9%	↑ 31.8%
Transfer to Upper Gluteus Maximus Muscle Thickness	↑ 20.7%	↑ 23.5%
Transfer to Lower Gluteus Maximus Muscle Thickness	↑ 20.3%	↑ 23.1%

However, it may be more beneficial for those individuals seeking greater mean and peak vastus lateralis EMG activity, total average force, eccentric average force,

total impulse, total work, total average power, repetition time, bar displacement, and transfer to vertical jump and squat strength to opt for the squat over the hip thrust.

It appears based on this thesis' findings that the direction of the force vectors in strength training influences the nature of transfer to strength and power tasks. Therefore, for maximum results, athletes should perform both squats and hip thrusts. Since squats and hip thrusts transfer over to one another, in times of injury where only one of the lifts can be performed, it is recommended that the one lift be performed in order to aid in the maintenance of strength of the other lift.

12.4 Future Research Directions

This thesis only scratches the surface and leads to the formation of many hypotheses that should be tested in the future. In terms of EMG research, a comprehensive study should be conducted to test the upper and lower gluteus maximus EMG activity using a variety of MVIC positions, especially in a highly trained male population. In addition, several comprehensive EMG studies should be undertaken to compare the upper and lower gluteus maximus activity between a variety of exercises and loading schemes. Suggested exercises include the Atlas stone lift, prone weighted bent-leg hip extension, barbell hip thrust, barbell glute bridge, back extension, reverse hyper, squat, deadlift, good morning, lunge, power clean, hex bar jump squat, sled push, and kettlebell swing. Finally, fine-wire EMG should be utilized in addition to surface EMG to determine the validity of surface EMG when examining gluteus maximus activity.

Furthermore, future acute research should be undertaken to:

1. Calculate the hip extension torque angle curve associated with the squat versus hip thrust using both inverse dynamics and quasi-static methods.
2. Calculate the band tension associated with band hip thrusts using a force plate.

3. Comprehensively measure the erector spinae, multifidi, abdominal, oblique, quadratus lumborum, rectus femoris, psoas, gluteal, hip rotator, adductor, vasti, hamstring, gastroc, and tibialis EMG activity between heavy squats and hip thrusts.
4. Compare the heart rate, metabolic, and hormonal responses between squats and hip thrusts.
5. Comprehensively measure concentric, eccentric, and total force, velocity, power, impulse, work, and rate of force development, in addition to load, set duration, and barbell displacement between squats and hip thrusts.
6. Determine the concentric, eccentric, and total joint power at the spine, knees, ankles, and hips between squats and hip thrusts.
7. Determine the levels of muscle damage and cell swelling associated with the squat and hip thrust using weighted T2 MRI.
8. Determine the active and passive muscle forces associated with squats and hip thrusts utilizing muscle modelling.
9. Determine whether the MHPT correlates with different measures of performance.

In addition, future longitudinal research should be undertaken to:

1. Examine the transfer of squats versus hip thrusts to deadlift strength.
2. Determine whether squats and/or hip thrusts alter deadlift kinematics.
3. Examine the transfer of squats versus hip thrusts to maximum velocity sprinting.
4. Examine the transfer of squats versus hip thrusts to long duration running.
5. Determine the exercises, methods, and protocols that best improve the MHPT.
6. Examine the transfer of squats versus hip thrust on gluteus maximus fascicle length, pennation angle, and moment arm.

7. Examine the transfer of squats versus hip thrusts on hip extension isometric torque at a variety of joint angles and isokinetic torque at a variety of speeds using an isokinetic dynamometer.
8. Determine whether hip thrusts indeed improve acceleration and/or speed via increased horizontal force production, or through another mechanism.

The randomized-controlled trials in this thesis should be duplicated with other populations pertaining to gender, age, and training status, and perhaps expanded upon to include more subjects, different loading schemes, combined groups, additional exercises, longer durations, and more measurements. In particular, the duplication of Chapter 7 with the utilization of male powerlifters and heavier loads would be beneficial. Moreover, the duplication of Chapter 10 with male adults, a combined squat and hip thrust group, and also including the MHPT, triple jump, and maximum velocity sprinting would be beneficial. Since the deadlift is a highly popular exercise, comparison studies between squats, deadlifts, and hip thrusts would be beneficial. Lastly, training studies utilizing MRI to measure changes in upper and lower gluteus maximus cross-sectional area and muscle volume between squats and hip thrusts are warranted.

Future research should test the force vector hypothesis with other exercises, activities, and vectors. For example, Olympic lifting variations and hex bar jump squats could be pitted against sled pushes and kettlebell swings, and lateral and rotational vectors such as cutting and swinging power could be tested as well. Should the force vector theory hold up over time, future research should be undertaken in order to determine the mechanisms responsible for the transfer specificity, possibly investigating various joint angle curves including EMG, moment of force, and joint power.

REFERENCES

(APA format)

- Adamson, G., & Whitney, R. (1971). *Critical appraisal of jumping as a measure of human power*. Karger Publishers.
- Alkjaer, T., Wieland, M. R., Andersen, M. S., Simonsen, E. B., & Rasmussen, J. (2012). Computational modeling of a forward lunge: Towards a better understanding of the function of the cruciate ligaments. *Journal of Anatomy*, 221(6), 590-597. doi:10.1111/j.1469-7580.2012.01569.x
- Anders, M. (2006). Glutes to the max. *ACE*, 7.
- Andersen, L. L., Magnusson, S. P., Nielsen, M., Haleem, J., Poulsen, K., & Aagaard, P. (2006). Neuromuscular activation in conventional therapeutic exercises and heavy resistance exercises: Implications for rehabilitation. *Physical Therapy*, 86(5), 683-697.
- Anderson, C. E., Sforzo, G. A., & Sigg, J. A. (2008). The effects of combining elastic and free weight resistance on strength and power in athletes. *Journal of Strength and Conditioning Research*, 22(2), 567-574. doi:10.1519/JSC.0b013e3181634d1e
- Armstrong, R. A. (2014). When to use the bonferroni correction. *Ophthalmic and Physiological Optics*, 34(5), 502-508. doi:10.1111/opo.12131
- Arnett, J. J. (1999). Adolescent storm and stress, reconsidered. *American Psychologist*, 54(5), 317-326.
- Aspe, R. R., & Swinton, P. A. (2014). Electromyographic and kinetic comparison of the back squat and overhead squat. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000000462
- Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, 26(4), 217-238.
- Augustsson, J., Thomee, R., Hornstedt, P., Lindblom, J., Karlsson, J., & Grimby, G. (2003). Effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise. *Journal of Strength and Conditioning Research*, 17(2), 411-416.
- Baechle, T. R., & Earle, R. W. (2008). *Essentials of strength training and conditioning* (3rd ed.). Champaign, IL: Human Kinetics.
- Bamman, M. M., Petrella, J. K., Kim, J. S., Mayhew, D. L., & Cross, J. M. (2007). Cluster analysis tests the importance of myogenic gene expression during myofiber hypertrophy in humans. *Journal of Applied Physiology*, 102(6), 2232-2239. doi:10.1152/japplphysiol.00024.2007
- Barak, Y., Ayalon, M., & Dvir, Z. (2004). Transferability of strength gains from limited to full range of motion. *Medicine and Science in Sports and Exercise*, 36(8), 1413-1420.
- Bartlett, J. L., Sumner, B., Ellis, R. G., & Kram, R. (2014). Activity and functions of the human gluteal muscles in walking, running, sprinting, and climbing. *American Journal of Physical Anthropology*, 153(1), 124-131. doi:10.1002/ajpa.22419
- Barton, C. J., Kennedy, A., Twycross-Lewis, R., Woledge, R., Malliaras, P., & Morrissey, D. (2014). Gluteal muscle activation during the isometric phase of squatting exercises with and without a swiss ball. *Physical Therapy in Sport* 15(1), 39-46. doi:10.1016/j.ptsp.2013.02.006
- Beardsley, C., & Contreras, B. (2014). The increasing role of the hip extensor musculature with heavier compound lower-body movements and more explosive sport actions. *Strength & Conditioning Journal*, 36(2), 49-55.

- Beckham, G., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., . . . Stone, M. (2013). Relationships of isometric mid-thigh pull variables to weightlifting performance. *Journal of Sports Medicine and Physical Fitness*, 53(5), 573-581.
- Behrens, M. J., & Simonson, S. R. (2011). A comparison of the various methods used to enhance sprint speed. *Strength & Conditioning Journal*, 33(2), 64-71.
- Bellar, D. M., Muller, M. D., Barkley, J. E., Kim, C. H., Ida, K., Ryan, E. J., . . . Glickman, E. L. (2011). The effects of combined elastic- and free-weight tension vs. Free-weight tension on one-repetition maximum strength in the bench press. *Journal of Strength and Conditioning Research*, 25(2), 459-463. doi:10.1519/JSC.0b013e3181c1f8b6
- Belli, A., Kyrolainen, H., & Komi, P. V. (2002). Moment and power of lower limb joints in running. *International Journal of Sports Medicine*, 23(2), 136-141. doi:10.1055/s-2002-20136
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, 289-300.
- Bezodis, I. N., Kerwin, D. G., & Salo, A. I. (2008). Lower-limb mechanics during the support phase of maximum-velocity sprint running. *Medicine and Science in Sports and Exercise*, 40(4), 707-715. doi:10.1249/MSS.0b013e318162d162
- Bird, S., & Barrington-Higgs, B. (2010). Exploring the deadlift. *Strength & Conditioning Journal*, 32(2), 46-51.
- Bird, S. P., & Casey, S. (2012). Exploring the front squat. *Strength & Conditioning Journal*, 34(2), 27-33.
- Blatnik, J. A., Goodman, C. L., Capps, C. R., Awelewa, O. O., Triplett, T. N., Erickson, T. M., & McBride, J. M. (2014). Effect of load on peak power of the bar, body and system during the deadlift. *Journal of Sports Science & Medicine*, 13(3), 511-515.
- Blazevich, A. J. (2000). Optimizing hip musculature for greater sprint running speed. *Strength & Conditioning Journal*, 22(2), 22.
- Blemker, S. S., & Delp, S. L. (2005). Three-dimensional representation of complex muscle architectures and geometries. *Annals of Biomedical Engineering*, 33(5), 661-673.
- Bloomquist, K., Langberg, H., Karlsen, S., Madsgaard, S., Boesen, M., & Raastad, T. (2013). Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *European Journal of Applied Physiology*, 113(8), 2133-2142. doi:10.1007/s00421-013-2642-7
- Boren, K., Conrey, C., Le Coguic, J., Paprocki, L., Voight, M., & Robinson, T. K. (2011). Electromyographic analysis of gluteus medius and gluteus maximus during rehabilitation exercises. *International Journal of Sports Physical Therapy*, 6(3), 206-223.
- Boudreau, S. N., Dwyer, M. K., Mattacola, C. G., Lattermann, C., Uhl, T. L., & McKeon, J. M. (2009). Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. *Journal of Sport Rehabilitation*, 18(1), 91-103.
- Braidot, A., Brusa, M., Lestussi, F., & Parera, G. (2007). *Biomechanics of front and back squat exercises*. Paper presented at the Journal of Physics: Conference Series.
- Bruder, C. E., Piotrowski, A., Gijsbers, A. A., Andersson, R., Erickson, S., Diaz de Stahl, T., . . . Dumanski, J. P. (2008). Phenotypically concordant and discordant monozygotic twins display different DNA copy-number-variation profiles. *American Journal of Human Genetics*, 82(3), 763-771. doi:10.1016/j.ajhg.2007.12.011

- Brughelli, M., & Cronin, J. (2008). Preventing hamstring injuries in sport. *Strength & Conditioning Journal*, 30(1), 55-64.
- Brughelli, M., Cronin, J., & Chaouachi, A. (2011a). Effects of running velocity on running kinetics and kinematics. *Journal of Strength and Conditioning Research*, 25(4), 933-939. doi:10.1519/JSC.0b013e3181c64308
- Brughelli, M., Cronin, J., & Chaouachi, A. (2011b). Effects of running velocity on running kinetics and kinematics. *The Journal of Strength & Conditioning Research*, 25(4), 933-939. doi:10.1519/JSC.0b013e3181c64308
- Brughelli, M., Mendiguchia, J., Nosaka, K., Idoate, F., Arcos, A. L., & Cronin, J. (2010). Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Physical Therapy in Sport* 11(2), 50-55. doi:10.1016/j.ptsp.2009.12.002
- Bryanton, M. A., Carey, J. P., Kennedy, M. D., & Chiu, L. Z. (2015). Quadriceps effort during squat exercise depends on hip extensor muscle strategy. *Sports Biomechanics*, 14(1), 122-138. doi:10.1080/14763141.2015.1024716
- Bryanton, M. A., Kennedy, M. D., Carey, J. P., & Chiu, L. Z. (2012). Effect of squat depth and barbell load on relative muscular effort in squatting. *Journal of Strength and Conditioning Research*, 26(10), 2820-2828. doi:10.1519/JSC.0b013e31826791a7
- Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., Al Haddad, H., Mendez-Villanueva, A., & Morin, J. B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *Journal of Sports Sciences*, 32(20), 1906-1913. doi:10.1080/02640414.2014.965191
- Busjahn, A., & Hur, Y. M. (2006). Twin registries: An ongoing success story. *Twin Research and Human Genetics*, 9(6), 705. doi:10.1375/183242706779462714
- Butterfield, T. A., Leonard, T. R., & Herzog, W. (2005). Differential serial sarcomere number adaptations in knee extensor muscles of rats is contraction type dependent. *Journal of Applied Physiology*, 99(4), 1352-1358. doi:10.1152/jappphysiol.00481.2005
- Calatayud, J., Borreani, S., Colado, J. C., Martin, F., Tella, V., & Andersen, L. L. (2014). Bench press and push-up at comparable levels of muscle activity results in similar strength gains. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000000589
- Cambridge, E. D., Sidorkewicz, N., Ikeda, D. M., & McGill, S. M. (2012). Progressive hip rehabilitation: The effects of resistance band placement on gluteal activation during two common exercises. *Clinical Biomechanics (Bristol, Avon)*, 27(7), 719-724. doi:10.1016/j.clinbiomech.2012.03.002
- Carlsson, L., Yu, J. G., Moza, M., Carpen, O., & Thornell, L. E. (2007). Myotilin: A prominent marker of myofibrillar remodelling. *Neuromuscular Disorders*, 17(1), 61-68. doi:10.1016/j.nmd.2006.09.007
- Caterisano, A., Moss, R. F., Pellingier, T. K., Woodruff, K., Lewis, V. C., Booth, W., & Khadra, T. (2002). The effect of back squat depth on the emg activity of 4 superficial hip and thigh muscles. *Journal of Strength and Conditioning Research*, 16(3), 428-432.
- Cavagna, G. A. (2006). The landing-take-off asymmetry in human running. *Journal of Experimental Biology*, 209(Pt 20), 4051-4060. doi:10.1242/jeb.02344
- Centeno, R. F. (2006). Gluteal aesthetic unit classification: A tool to improve outcomes in body contouring. *Aesthetic Surgery Journal*, 26(2), 200-208. doi:10.1016/j.asj.2006.01.001
- Channell, B. T., & Barfield, J. P. (2008). Effect of olympic and traditional resistance training on vertical jump improvement in high school boys. *Journal of Strength*

- and *Conditioning Research*, 22(5), 1522-1527.
doi:10.1519/JSC.0b013e318181a3d0
- Chelly, M. S., Cherif, N., Amar, M. B., Hermassi, S., Fathloun, M., Bouhlel, E., . . . Shephard, R. J. (2010). Relationships of peak leg power, 1 maximal repetition half back squat, and leg muscle volume to 5-m sprint performance of junior soccer players. *Journal of Strength and Conditioning Research*, 24(1), 266-271. doi:10.1519/JSC.0b013e3181c3b298
- Choi, S. A., Cynn, H. S., Yi, C. H., Kwon, O. Y., Yoon, T. L., Choi, W. J., & Lee, J. H. (2014). Isometric hip abduction using a thera-band alters gluteus maximus muscle activity and the anterior pelvic tilt angle during bridging exercise. *Journal of Electromyography and Kinesiology*. doi:10.1016/j.jelekin.2014.09.005
- Clark, D. R., Lambert, M. I., & Hunter, A. M. (2012). Muscle activation in the loaded free barbell squat: A brief review. *Journal of Strength and Conditioning Research*, 26(4), 1169-1178. doi:10.1519/JSC.0b013e31822d533d
- Clark, R. A., Humphries, B., Hohmann, E., & Bryant, A. L. (2011). The influence of variable range of motion training on neuromuscular performance and control of external loads. *Journal of Strength and Conditioning Research*, 25(3), 704-711. doi:10.1519/JSC.0b013e3181c6a0ff
- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*: Routledge Academic.
- Comfort, P., Allen, M., & Graham-Smith, P. (2011a). Comparisons of peak ground reaction force and rate of force development during variations of the power clean. *Journal of Strength and Conditioning Research*, 25(5), 1235-1239. doi:10.1519/JSC.0b013e3181d6dc0d
- Comfort, P., Allen, M., & Graham-Smith, P. (2011b). Kinetic comparisons during variations of the power clean. *Journal of Strength and Conditioning Research*, 25(12), 3269-3273. doi:10.1519/JSC.0b013e3182184dea
- Comfort, P., Bullock, N., & Pearson, S. J. (2012). A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *Journal of Strength and Conditioning Research*, 26(4), 937-940. doi:10.1519/JSC.0b013e31822e5889
- Comfort, P., Jones, P. A., McMahon, J. J., & Newton, R. (2015). Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: Test-retest reliability. *International Journal of Sports Physiology and Performance*, 10(1), 58-63. doi:10.1123/ijsp.2014-0077
- Comfort, P., Pearson, S. J., & Mather, D. (2011). An electromyographical comparison of trunk muscle activity during isometric trunk and dynamic strengthening exercises. *Journal of Strength and Conditioning Research*, 25(1), 149-154. doi:10.1519/JSC.0b013e3181fb412f
- Contreras, B., Cronin, J., & Schoenfeld, B. (2011). Barbell hip thrust. *Strength & Conditioning Journal*, 33(5), 58-61. doi:10.1519/SSC.0b013e31822fa09d
- Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (2015a). A comparison of gluteus maximus, biceps femoris, and vastus lateralis emg activity in the back squat and barbell hip thrust exercises. *Journal of Applied Biomechanics*. doi:10.1123/jab.2014-0301
- Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (2015b). A comparison of gluteus maximus, biceps femoris, and vastus lateralis emg amplitude in the parallel, full, and front squat variations in resistance trained females. *Journal of Applied Biomechanics*.

- Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (In Review). Reliability of the maximum horizontal push test. *Journal of Applied Biomechanics*.
- Contreras, B. M., Cronin, J. B., Schoenfeld, B. J., Nates, R. J., & Sonmez, G. T. (2013). Are all hip extension exercises created equal? *Strength & Conditioning Journal*, 35(2), 17-22.
- Cook, C. J., & Crewther, B. T. (2012). Changes in salivary testosterone concentrations and subsequent voluntary squat performance following the presentation of short video clips. *Hormones and Behavior*, 61(1), 17-22.
doi:10.1016/j.yhbeh.2011.09.006
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2007). The influence of body mass on calculation of power during lower-body resistance exercises. *Journal of Strength and Conditioning Research*, 21(4), 1042-1049. doi:10.1519/R-21636.1
- Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics*, 24(2), 112-120.
- Costello, J. T., Bieuzen, F., & Bleakley, C. M. (2014). Where are all the female participants in sports and exercise medicine research? *European Journal of Sport Science*, 14(8), 847-851. doi:10.1080/17461391.2014.911354
- Cotter, J. A., Chaudhari, A. M., Jamison, S. T., & Devor, S. T. (2010). Differences in rate of increased patellofemoral joint reaction force in the back squat exercise. *Medicine and Science in Sports and Exercise*, 42(5), 681.
- Cotter, J. A., Chaudhari, A. M., Jamison, S. T., & Devor, S. T. (2013). Knee joint kinetics in relation to commonly prescribed squat loads and depths. *Journal of Strength and Conditioning Research*, 27(7), 1765-1774.
doi:10.1519/JSC.0b013e3182773319
- Crewther, B. T., Cronin, J., & Keogh, J. W. (2008). The contribution of volume, technique, and load to single-repetition and total-repetition kinematics and kinetics in response to three loading schemes. *Journal of Strength and Conditioning Research*, 22(6), 1908-1915. doi:10.1519/JSC.0b013e3181839f61
- Cronin, J., McNair, P. J., & Marshall, R. N. (2001). Developing explosive power: A comparison of technique and training. *Journal of Science and Medicine in Sport*, 4(1), 59-70.
- Cronin, J., Ogden, T., & Lawton, T. (2007). Does increasing maximal strength improve sprint running performance? *Strength & Conditioning Journal*, 29(3), 86-95.
doi:10.1097/00126548-200706000-00014
- Cronin, J. B., McNair, P. J., & Marshall, R. N. (2003). Force-velocity analysis of strength-training techniques and load: Implications for training strategy and research. *Journal of Strength and Conditioning Research*, 17(1), 148-155.
- Crow, J. F., Buttifant, D., Kearny, S. G., & Hrysomallis, C. (2012). Low load exercises targeting the gluteal muscle group acutely enhance explosive power output in elite athletes. *Journal of Strength and Conditioning Research*, 26(2), 438-442.
doi:10.1519/JSC.0b013e318220dfab
- Cuenca-Guerra, R., & Lugo-Beltran, I. (2006). Beautiful buttocks: Characteristics and surgical techniques. *Clinics in Plastic Surgery*, 33(3), 321-332.
doi:10.1016/j.cps.2006.04.002
- Cuenca-Guerra, R., & Quezada, J. (2004). What makes buttocks beautiful? A review and classification of the determinants of gluteal beauty and the surgical techniques to achieve them. *Aesthetic Plastic Surgery*, 28(5), 340-347.
doi:10.1007/s00266-004-3114-6
- Cuk, I., Markovic, M., Nedeljkovic, A., Ugarkovic, D., Kukolj, M., & Jaric, S. (2014). Force-velocity relationship of leg extensors obtained from loaded and unloaded

- vertical jumps. *European Journal of Applied Physiology*, 114(8), 1703-1714.
doi:10.1007/s00421-014-2901-2
- Cunningham, D. J., West, D. J., Owen, N. J., Shearer, D. A., Finn, C. V., Bracken, R. M., . . . Kilduff, L. P. (2013). Strength and power predictors of sprinting performance in professional rugby players. *Journal of Sports Medicine and Physical Fitness*, 53(2), 105-111.
- Czaprowski, D., Afeltowicz, A., Gebicka, A., Pawlowska, P., Kedra, A., Barrios, C., & Hadala, M. (2014). Abdominal muscle emg-activity during bridge exercises on stable and unstable surfaces. *Physical Therapy in Sport* 15(3), 162-168.
doi:10.1016/j.ptsp.2013.09.003
- Dawes, J., & Lentz, D. (2012). Methods of developing power to improve acceleration for the non-track athlete. *Strength & Conditioning Journal*, 34(6), 44-51.
- de Lacey, J., Brughelli, M. E., McGuigan, M. R., & Hansen, K. T. (2014). Strength, speed and power characteristics of elite rugby league players. *Journal of Strength and Conditioning Research*, 28(8), 2372-2375.
doi:10.1519/JSC.0000000000000397
- De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13, 135-163.
- De Ridder, E. M., Van Oosterwijck, J. O., Vleeming, A., Vanderstraeten, G. G., & Danneels, L. A. (2013). Posterior muscle chain activity during various extension exercises: An observational study. *BMC Musculoskeletal Disorders*, 14, 204.
doi:10.1186/1471-2474-14-204
- Dennis, R. A., Zhu, H., Kortebein, P. M., Bush, H. M., Harvey, J. F., Sullivan, D. H., & Peterson, C. A. (2009). Muscle expression of genes associated with inflammation, growth, and remodeling is strongly correlated in older adults with resistance training outcomes. *Physiological Genomics*, 38(2), 169-175.
doi:10.1152/physiolgenomics.00056.2009
- Dias, J. A., Dal Pupo, J., Reis, D. C., Borges, L., Santos, S. G., Moro, A. R., & Borges, N. G., Jr. (2011). Validity of two methods for estimation of vertical jump height. *Journal of Strength and Conditioning Research*, 25(7), 2034-2039.
doi:10.1519/JSC.0b013e3181e73f6e
- Diggin, D., O'Regan, C., Whelan, N., Daly, S., McLoughlin, V., McNamara, L., & Reilly, A. (2011). *A biomechanical analysis of front versus back squat: Injury implications*. Paper presented at the ISBS-Conference Proceedings Archive.
- Dimitrova, N. A., & Dimitrov, G. V. (2003). Interpretation of emg changes with fatigue: Facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology*, 13(1), 13-36.
- DiStefano, L. J., Padua, D. A., Blackburn, J. T., Garrett, W. E., Guskiewicz, K. M., & Marshall, S. W. (2010). Integrated injury prevention program improves balance and vertical jump height in children. *Journal of Strength and Conditioning Research*, 24(2), 332-342. doi:10.1519/JSC.0b013e3181cc2225
- Dorn, T. W., Schache, A. G., & Pandy, M. G. (2012). Muscular strategy shift in human running: Dependence of running speed on hip and ankle muscle performance. *Journal of Experimental Biology*, 215(Pt 11), 1944-1956.
doi:10.1242/jeb.064527
- Dostal, W. F., Soderberg, G. L., & Andrews, J. G. (1986). Actions of hip muscles. *Physical Therapy*, 66(3), 351-361.
- Drezewska, M., Galuszka, R., & Sliwinski, Z. (2012). Hip joint mobility in dancers: Preliminary report. *Ortopedia Traumatologia Rehabilitacja*, 14(5), 443-452.
doi:10.5604/15093492.1012503
- Drinkwater, E. J., Lawton, T. W., Lindsell, R. P., Pyne, D. B., Hunt, P. H., & McKenna, M. J. (2005). Training leading to repetition failure enhances bench press

- strength gains in elite junior athletes. *Journal of Strength and Conditioning Research*, 19(2), 382-388. doi:10.1519/R-15224.1
- Drinkwater, E. J., Moore, N. R., & Bird, S. P. (2012). Effects of changing from full range of motion to partial range of motion on squat kinetics. *Journal of Strength and Conditioning Research*, 26(4), 890-896. doi:10.1519/JSC.0b013e318248ad2e
- Duehring, M. D., Feldmann, C. R., & Ebben, W. P. (2009). Strength and conditioning practices of united states high school strength and conditioning coaches. *Journal of Strength and Conditioning Research*, 23(8), 2188-2203. doi:10.1519/JSC.0b013e3181bac62d
- Dunn, I. F., Proctor, M. R., & Day, A. L. (2006). Lumbar spine injuries in athletes. *Neurosurgical Focus*, 21(4), E4.
- Ebben, W. P., & Blackard, D. O. (2001). Strength and conditioning practices of national football league strength and conditioning coaches. *Journal of Strength and Conditioning Research*, 15(1), 48-58.
- Ebben, W. P., Carroll, R. M., & Simenz, C. J. (2004). Strength and conditioning practices of national hockey league strength and conditioning coaches. *Journal of Strength and Conditioning Research*, 18(4), 889-897. doi:10.1519/14133.1
- Ebben, W. P., Feldmann, C. R., Dayne, A., Mitsche, D., Alexander, P., & Knetzger, K. J. (2009). Muscle activation during lower body resistance training. *International Journal of Sports Medicine*, 30(1), 1-8. doi:10.1055/s-2008-1038785
- Ebben, W. P., Hintz, M. J., & Simenz, C. J. (2005). Strength and conditioning practices of major league baseball strength and conditioning coaches. *Journal of Strength and Conditioning Research*, 19(3), 538-546. doi:10.1519/R-15464.1
- Ebben, W. P., & Jensen, R. L. (2002). Electromyographic and kinetic analysis of traditional, chain, and elastic band squats. *Journal of Strength and Conditioning Research*, 16(4), 547-550.
- Ebben, W. P., Leigh, D. H., & Jensen, R. L. (2000). The role of the back squat as a hamstring training stimulus. *Strength & Conditioning Journal*, 22(5), 15.
- Eckert, R. M., & Snarr, R. L. (2014). Barbell hip thrust. *Journal of Sport and Human Performance*, 2(2).
- Elson, R., & Aspinall, G. (2008). Measurement of hip range of flexion-extension and straight-leg raising. *Clinical Orthopaedics and Related Research*, 466(2), 281-286. doi:10.1007/s11999-007-0073-7
- Emami, M., Arab, A. M., & Ghamkhar, L. (2014). The activity pattern of the lumbo-pelvic muscles during prone hip extension in athletes with and without hamstring strain injury. *International Journal of Sports Physical Therapy*, 9(3), 312-319.
- Enoka, R. M., & Duchateau, J. (2015). Inappropriate interpretation of surface emg signals and muscle fiber characteristics impedes progress on understanding the control of neuromuscular function. *Journal of Applied Physiology*, jap 00280 02015. doi:10.1152/jappphysiol.00280.2015
- Escamilla, R. F. (2001). Knee biomechanics of the dynamic squat exercise. *Medicine and Science in Sports and Exercise*, 33(1), 127-141.
- Escamilla, R. F., Fleisig, G. S., Lowry, T. M., Barrentine, S. W., & Andrews, J. R. (2001). A three-dimensional biomechanical analysis of the squat during varying stance widths. *Medicine and Science in Sports and Exercise*, 33(6), 984-998.
- Escamilla, R. F., Fleisig, G. S., Zheng, N., Barrentine, S. W., Wilk, K. E., & Andrews, J. R. (1998). Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Medicine and Science in Sports and Exercise*, 30(4), 556-569.

- Escamilla, R. F., Fleisig, G. S., Zheng, N., Lander, J. E., Barrentine, S. W., Andrews, J. R., . . . Moorman, C. T., 3rd. (2001). Effects of technique variations on knee biomechanics during the squat and leg press. *Medicine and Science in Sports and Exercise*, 33(9), 1552-1566.
- Escamilla, R. F., Francisco, A. C., Fleisig, G. S., Barrentine, S. W., Welch, C. M., Kayes, A. V., . . . Andrews, J. R. (2000). A three-dimensional biomechanical analysis of sumo and conventional style deadlifts. *Medicine and Science in Sports and Exercise*, 32(7), 1265-1275.
- Escamilla, R. F., Francisco, A. C., Kayes, A. V., Speer, K. P., & Moorman, C. T., 3rd. (2002). An electromyographic analysis of sumo and conventional style deadlifts. *Medicine and Science in Sports and Exercise*, 34(4), 682-688.
- Esformes, J. I., & Bampouras, T. M. (2013). Effect of back squat depth on lower-body postactivation potentiation. *Journal of Strength and Conditioning Research*, 27(11), 2997-3000. doi:10.1519/JSC.0b013e31828d4465
- Fischer, F. J., & Houtz, S. J. (1968). Evaluation of the function of the gluteus maximus muscle. An electromyographic study. *American Journal of Physical Medicine*, 47(4), 182-191.
- Flanagan, S. P., & Salem, G. J. (2007). Bilateral differences in the net joint torques during the squat exercise. *Journal of Strength and Conditioning Research*, 21(4), 1220-1226. doi:10.1519/R-21156.1
- Fonseca, R. M., Roschel, H., Tricoli, V., de Souza, E. O., Wilson, J. M., Laurentino, G. C., . . . Ugrinowitsch, C. (2014). Changes in exercises are more effective than in loading schemes to improve muscle strength. *Journal of Strength and Conditioning Research*, 28(11), 3085-3092. doi:10.1519/JSC.0000000000000539
- Frost, D. M., Beach, T., Fenwick, C., Callaghan, J., & McGill, S. (2012). Is there a low-back cost to hip-centric exercise? Quantifying the lumbar spine joint compression and shear forces during movements used to overload the hips. *Journal of Sports Sciences*, 30(9), 859-870. doi:10.1080/02640414.2012.671532
- Fujisawa, H., Suzuki, H., Yamaguchi, E., Yoshiki, H., Wada, Y., & Watanabe, A. (2014). Hip muscle activity during isometric contraction of hip abduction. *Journal of Physical Therapy Science*, 26(2), 187-190. doi:10.1589/jpts.26.187
- Fukumoto, Y., Ikezoe, T., Tateuchi, H., Tsukagoshi, R., Akiyama, H., So, K., . . . Ichihashi, N. (2012). Muscle mass and composition of the hip, thigh and abdominal muscles in women with and without hip osteoarthritis. *Ultrasound in Medicine and Biology*, 38(9), 1540-1545. doi:10.1016/j.ultrasmedbio.2012.04.016
- Funato, K., Yanagiya, T., & Fukunaga, T. (2001). Ergometry for estimation of mechanical power output in sprinting in humans using a newly developed self-driven treadmill. *European Journal of Applied Physiology*, 84(3), 169-173. doi:10.1007/PL00007955
- Garcia-Masso, X., Colado, J. C., Gonzalez, L. M., Salva, P., Alves, J., Tella, V., & Triplett, N. T. (2011). Myoelectric activation and kinetics of different plyometric push-up exercises. *Journal of Strength and Conditioning Research*, 25(7), 2040-2047. doi:10.1519/JSC.0b013e3181e4f7ce
- Girard, O., Brocherie, F., Morin, J. B., Degache, F., & Millet, G. P. (2015). Comparison of four sections for analysing running mechanics alterations during repeated treadmill sprints. *Journal of Applied Biomechanics*. doi:10.1123/jab.2015-0049
- Gittoes, M. J., & Wilson, C. (2010). Intralimb joint coordination patterns of the lower extremity in maximal velocity phase sprint running. *Journal of Applied Biomechanics*, 26(2), 188-195.

- Gomes, W. A., Brown, L. E., Soares, E. G., Silva, J. J., Silva, F. H., Serpa, E. P., . . . Marchetti, P. H. (2015). Kinematic and semg analysis of the back squat at different intensities with and without knee wraps. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000000922
- Gorsuch, J., Long, J., Miller, K., Primeau, K., Rutledge, S., Sossong, A., & Durocher, J. J. (2013). The effect of squat depth on multiarticular muscle activation in collegiate cross-country runners. *Journal of Strength and Conditioning Research*, 27(9), 2619-2625. doi:10.1519/JSC.0b013e31828055d5
- Graham, J. F. (2000). Power clean. *Strength & Conditioning Journal*, 22(6), 63.
- Graham, J. F. (2004). Leg press. *Strength & Conditioning Journal*, 26(3), 53-54.
- Graham, J. F. (2011). Exercise: Barbell backward lunge. *Strength & Conditioning Journal*, 33(4), 80-82.
- Gullett, J. C., Tillman, M. D., Gutierrez, G. M., & Chow, J. W. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *Journal of Strength and Conditioning Research*, 23(1), 284-292. doi:10.1519/JSC.0b013e31818546bb
- Guskiewicz, K., Lephart, S., & Burkholder, R. (1993). The relationship between sprint speed and hip flexion/extension strength in collegiate athletes. *Isokinetics and Exercise Science*, 3(2), 111-116.
- Halaki, M., & Ginn, K. (2012). *Normalization of emg signals: To normalize or not to normalize and what to normalize to?* : INTECH Open Access Publisher.
- Hanson, E. D., Leigh, S., & Mynark, R. G. (2007). Acute effects of heavy- and light-load squat exercise on the kinetic measures of vertical jumping. *Journal of Strength and Conditioning Research*, 21(4), 1012-1017. doi:10.1519/R-20716.1
- Harman, E. A., Rosenstein, M. T., Frykman, P. N., & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine and Science in Sports and Exercise*, 22(6), 825-833.
- Hartmann, H., Wirth, K., & Klusemann, M. (2013). Analysis of the load on the knee joint and vertebral column with changes in squatting depth and weight load. *Sports Medicine*, 43(10), 993-1008. doi:10.1007/s40279-013-0073-6
- Hartmann, H., Wirth, K., Klusemann, M., Dalic, J., Matuschek, C., & Schmidtbleicher, D. (2012). Influence of squatting depth on jumping performance. *Journal of Strength and Conditioning Research*, 26(12), 3243-3261. doi:10.1519/JSC.0b013e31824ede62
- Healy, R., & Harrison, A. J. (2014). The effects of a unilateral gluteal activation protocol on single leg drop jump performance. *Sports Biomechanics*, 13(1), 33-46. doi:10.1080/14763141.2013.872288
- Hermens, H. J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., . . . Hägg, G. (1999). European recommendations for surface electromyography. *Roessingh Research and Development, Enschede*.
- Hislop, H., Avers, D., & Brown, M. (2013). *Daniels and worthingham's muscle testing: Techniques of manual examination and performance testing*: Elsevier Health Sciences.
- Hoffman, J. R., Cooper, J., Wendell, M., & Kang, J. (2004). Comparison of olympic vs. Traditional power lifting training programs in football players. *Journal of Strength and Conditioning Research*, 18(1), 129-135.
- Hoffman, J. R., Ratamess, N. A., & Kang, J. (2011). Performance changes during a college playing career in ncaa division iii football athletes. *Journal of Strength and Conditioning Research*, 25(9), 2351-2357. doi:10.1519/JSC.0b013e31821743df
- Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian journal of statistics*, 65-70.

- Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, 30(1), 1-15.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, 41(1), 3-13. doi:10.1249/MSS.0b013e31818cb278
- Hubal, M. J., Gordish-Dressman, H., Thompson, P. D., Price, T. B., Hoffman, E. P., Angelopoulos, T. J., . . . Clarkson, P. M. (2005). Variability in muscle size and strength gain after unilateral resistance training. *Medicine and Science in Sports and Exercise*, 37(6), 964-972.
- Hubley, C. L., & Wells, R. P. (1983). A work-energy approach to determine individual joint contributions to vertical jump performance. *European Journal of Applied Physiology and Occupational Physiology*, 50(2), 247-254.
- Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, 21(1), 31-43.
- Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011a). Age-related muscle atrophy in the lower extremities and daily physical activity in elderly women. *Archives of Gerontology and Geriatrics*, 53(2), e153-157. doi:10.1016/j.archger.2010.08.003
- Ikezoe, T., Mori, N., Nakamura, M., & Ichihashi, N. (2011b). Atrophy of the lower limbs in elderly women: Is it related to walking ability? *European Journal of Applied Physiology*, 111(6), 989-995. doi:10.1007/s00421-010-1728-8
- Inaba, Y., Yoshioka, S., Iida, Y., Hay, D. C., & Fukashiro, S. (2013). A biomechanical study of side steps at different distances. *Journal of Applied Biomechanics*, 29(3), 336-345.
- Isear, J. A., Jr., Erickson, J. C., & Worrell, T. W. (1997). Emg analysis of lower extremity muscle recruitment patterns during an unloaded squat. *Medicine and Science in Sports and Exercise*, 29(4), 532-539.
- Israetel, M. A., McBride, J. M., Nuzzo, J. L., Skinner, J. W., & Dayne, A. M. (2010). Kinetic and kinematic differences between squats performed with and without elastic bands. *Journal of Strength and Conditioning Research*, 24(1), 190-194. doi:10.1519/JSC.0b013e31819b7995
- Ito, A., Fukuda, K., & Kijima, K. (2008). Mid-phase movements of tyson gay and asafa powell in the 100 metres at the 2007 world championships in athletics. *New Studies in Athletics*, 23(2), 39-43.
- Jacobson, B. H., Conchola, E. G., Glass, R. G., & Thompson, B. J. (2013). Longitudinal morphological and performance profiles for american, ncaa division i football players. *Journal of Strength and Conditioning Research*, 27(9), 2347-2354. doi:10.1519/JSC.0b013e31827fcc7d
- Jakobsen, M. D., Sundstrup, E., Andersen, C. H., Aagaard, P., & Andersen, L. L. (2013). Muscle activity during leg strengthening exercise using free weights and elastic resistance: Effects of ballistic vs controlled contractions. *Human movement science*, 32(1), 65-78. doi:10.1016/j.humov.2012.07.002
- Jang, E. M., Kim, M. H., & Oh, J. S. (2013). Effects of a bridging exercise with hip adduction on the emg activities of the abdominal and hip extensor muscles in females. *Journal of Physical Therapy Science*, 25(9), 1147-1149. doi:10.1589/jpts.25.1147
- Jones, M. T., Ambegaonkar, J. P., Nindl, B. C., Smith, J. A., & Headley, S. A. (2012). Effects of unilateral and bilateral lower-body heavy resistance exercise on muscle activity and testosterone responses. *Journal of Strength and Conditioning Research*, 26(4), 1094-1100. doi:10.1519/JSC.0b013e318248ab3b

- Jonhagen, S., Ericson, M. O., Nemeth, G., & Eriksson, E. (1996). Amplitude and timing of electromyographic activity during sprinting. *Scandinavian Journal of Medicine and Science in Sports*, 6(1), 15-21.
- Juneja, H., Verma, S., & Khanna, G. (2010). Isometric strength and its relationship to dynamic performance: A systematic. *Journal of Exercise Science and Physiotherapy*, 6(2), 60-69.
- Kalb, J. S., & Hunter, G. R. (1991). Weight training economy as a function of intensity of the squat and overhead press exercise. *Journal of Sports Medicine and Physical Fitness*, 31(2), 154-160.
- Kang, S. Y., Jeon, H. S., Kwon, O., Cynn, H. S., & Choi, B. (2013). Activation of the gluteus maximus and hamstring muscles during prone hip extension with knee flexion in three hip abduction positions. *Manual Therapy*, 18(4), 303-307. doi:10.1016/j.math.2012.11.006
- Karlsson, E., & Jonsson, B. (1965). Function of the gluteus maximus muscle. An electromyographic study. *Acta Morphologica Neerlando-Scandinavica*, 6, 161-169.
- Kawamori, N., & Haff, G. G. (2004). The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research*, 18(3), 675-684. doi:10.1519/1533-4287(2004)18<675:TOTLFT>2.0.CO;2
- Kawamori, N., Nosaka, K., & Newton, R. U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *Journal of Strength and Conditioning Research*, 27(3), 568-573. doi:10.1519/JSC.0b013e318257805a
- Kawamori, N., Rossi, S. J., Justice, B. D., Haff, E. E., Pistilli, E. E., O'Bryant, H. S., . . . Haff, G. G. (2006). Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *Journal of Strength and Conditioning Research*, 20(3), 483-491. doi:10.1519/18025.1
- Kendall, F. P., McCreary, E. K., Provance, P. G., Rodgers, M. M., & Romani, W. (1993). Muscles, testing and function: With posture and pain.
- Kim, T. W., & Kim, Y. W. (2015). Effects of abdominal drawing-in during prone hip extension on the muscle activities of the hamstring, gluteus maximus, and lumbar erector spinae in subjects with lumbar hyperlordosis. *Journal of Physical Therapy Science*, 27(2), 383-386. doi:10.1589/jpts.27.383
- Kinugasa, T., Cerin, E., & Hooper, S. (2004). Single-subject research designs and data analyses for assessing elite athletes' conditioning. *Sports Medicine*, 34(15), 1035-1050.
- Kirby, T. J., McBride, J. M., Haines, T. L., & Dayne, A. M. (2011). Relative net vertical impulse determines jumping performance. *Journal of Applied Biomechanics*, 27(3), 207-214.
- Kong, P. W., & Van Haselen, J. (2010). Revisiting the influence of hip and knee angles on quadriceps excitation measured by surface electromyography: Original research article. *International SportMed Journal*, 11(2), 313-323.
- Kraemer, W. J., Adams, K., Cafarelli, E., Dudley, G. A., Dooly, C., Feigenbaum, M. S., . . . American College of Sports, M. (2002). American college of sports medicine position stand. Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise*, 34(2), 364-380.
- Kubo, K., Ohgo, K., Takeishi, R., Yoshinaga, K., Tsunoda, N., Kanehisa, H., & Fukunaga, T. (2006). Effects of isometric training at different knee angles on the muscle-tendon complex in vivo. *Scandinavian Journal of Medicine and Science in Sports*, 16(3), 159-167. doi:10.1111/j.1600-0838.2005.00450.x

- Kugler, F., & Janshen, L. (2010). Body position determines propulsive forces in accelerated running. *Journal of Biomechanics*, 43(2), 343-348. doi:10.1016/j.jbiomech.2009.07.041
- Kuitunen, S., Komi, P. V., & Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise*, 34(1), 166-173.
- Kwon, Y. J., & Lee, H. O. (2013). How different knee flexion angles influence the hip extensor in the prone position. *Journal of Physical Therapy Science*, 25(10), 1295-1297. doi:10.1589/jpts.25.1295
- Kyrolainen, H., Avela, J., & Komi, P. V. (2005). Changes in muscle activity with increasing running speed. *Journal of Sports Sciences*, 23(10), 1101-1109. doi:10.1080/02640410400021575
- Kyröläinen, H., Komi, P. V., & Belli, A. (1999). Changes in muscle activity patterns and kinetics with increasing running speed. *The Journal of Strength & Conditioning Research*, 13(4), 400-406.
- Lake, J. P., Carden, P. J., & Shorter, K. A. (2012). Wearing knee wraps affects mechanical output and performance characteristics of back squat exercise. *Journal of Strength and Conditioning Research*, 26(10), 2844-2849. doi:10.1519/JSC.0b013e3182429840
- Lake, J. P., Hetzler, B. S., & Lauder, M. A. (2014). Magnitude and relative distribution of kettlebell snatch force-time characteristics. *Journal of Strength and Conditioning Research*, 28(11), 3063-3072. doi:10.1519/JSC.0000000000000538
- Lake, J. P., & Lauder, M. A. (2012). Mechanical demands of kettlebell swing exercise. *Journal of Strength and Conditioning Research*, 26(12), 3209-3216. doi:10.1519/JSC.0b013e3182474280
- Lake, J. P., Mundy, P. D., & Comfort, P. (2014). Power and impulse applied during push press exercise. *Journal of Strength and Conditioning Research*, 28(9), 2552-2559. doi:10.1519/JSC.0000000000000438
- Lamontagne, M., Kennedy, M. J., & Beaulé, P. E. (2009). The effect of cam fai on hip and pelvic motion during maximum squat. *Clinical Orthopaedics and Related Research*, 467(3), 645-650. doi:10.1007/s11999-008-0620-x
- Lander, J. E., Simonton, R. L., & Giacobbe, J. K. (1990). The effectiveness of weight-belts during the squat exercise. *Medicine and Science in Sports and Exercise*, 22(1), 117-126.
- Lenetsky, S., Harris, N., & Brughelli, M. (2013). Assessment and contributors of punching forces in combat sports athletes: Implications for strength and conditioning. *Strength & Conditioning Journal*, 35(2), 1-7.
- Leonard, T. R., & Herzog, W. (2010). Regulation of muscle force in the absence of actin-myosin-based cross-bridge interaction. *American Journal of Physiology: Cell Physiology*, 299(1), C14-20. doi:10.1152/ajpcell.00049.2010
- Lewis, C. L., & Sahrman, S. A. (2009). Muscle activation and movement patterns during prone hip extension exercise in women. *Journal of Athletic Training*, 44(3), 238-248. doi:10.4085/1062-6050-44.3.238
- Lieber, R. L., & Friden, J. (1993). Muscle damage is not a function of muscle force but active muscle strain. *Journal of Applied Physiology*, 74(2), 520-526.
- Lockie, R. G., Murphy, A. J., Schultz, A. B., Knight, T. J., & Janse de Jonge, X. A. (2012). The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *Journal of Strength and Conditioning Research*, 26(6), 1539-1550. doi:10.1519/JSC.0b013e318234e8a0
- Los Arcos, A., Yanci, J., Mendiguchia, J., Salinero, J. J., Brughelli, M., & Castagna, C. (2014). Short-term training effects of vertically and horizontally oriented

- exercises on neuromuscular performance in professional soccer players. *International Journal of Sports Physiology and Performance*, 9(3), 480-488. doi:10.1123/ijsp.2013-0063
- Lynn, S. K., & Noffal, G. J. (2012). Lower extremity biomechanics during a regular and counterbalanced squat. *Journal of Strength and Conditioning Research*, 26(9), 2417-2425. doi:10.1519/JSC.0b013e31823f8c2d
- Lyons, K., Perry, J., Gronley, J. K., Barnes, L., & Antonelli, D. (1983). Timing and relative intensity of hip extensor and abductor muscle action during level and stair ambulation. An emg study. *Physical Therapy*, 63(10), 1597-1605.
- MacAskill, M. J., Durant, T. J., & Wallace, D. A. (2014). Gluteal muscle activity during weightbearing and non-weightbearing exercise. *International Journal of Sports Physical Therapy*, 9(7), 907-914.
- Mackala, K., Stodolka, J., Siemienski, A., & Coh, M. (2013a). Biomechanical analysis of squat jump and countermovement jump from varying starting positions. *Journal of Strength and Conditioning Research*, 27(10), 2650-2661. doi:10.1519/JSC.0b013e31828909ec
- Mackala, K., Stodolka, J., Siemienski, A., & Coh, M. (2013b). Biomechanical analysis of standing long jump from varying starting positions. *Journal of Strength and Conditioning Research*, 27(10), 2674-2684. doi:10.1519/JSC.0b013e31825fce65
- Manabe, Y., Shimada, K., & Ogata, M. (2007). Effect of slow movement and stretch-shortening cycle on lower extremity muscle activity and joint moments during squat. *Journal of Sports Medicine and Physical Fitness*, 47(1), 1-12.
- Mangine, G. T., Hoffman, J. R., Gonzalez, A. M., Wells, A. J., Townsend, J. R., Jajtner, A. R., . . . Stout, J. R. (2013). Speed, force and power values produced from a non-motorized treadmill test are related to sprinting performance. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000000316
- Mann, R. V. (1981). A kinetic analysis of sprinting. *Medicine and Science in Sports and Exercise*, 13(5), 325-328.
- Marques, M. C., Izquierdo, M., Marinho, D. A., Barbosa, T. M., Ferraz, R., & Gonzalez-Badillo, J. J. (2015). Association between force-time curve characteristics and vertical jump performance in trained athletes. *Journal of Strength and Conditioning Research*, 29(7), 2045-2049. doi:10.1519/JSC.0000000000000739
- Martinez-Valencia, M. A., Gonzalez-Rave, J. M., Santos-Garcia, D. J., Alcaraz Ramon, P. E., & Navarro-Valdivielso, F. (2014). Interrelationships between different loads in resisted sprints, half-squat 1 rm and kinematic variables in trained athletes. *European Journal of Sport Science*, 14 Suppl 1, S18-24. doi:10.1080/17461391.2011.638935
- Marzke, M. W., Longhill, J. M., & Rasmussen, S. A. (1988). Gluteus maximus muscle function and the origin of hominid bipedality. *American Journal of Physical Anthropology*, 77(4), 519-528. doi:10.1002/ajpa.1330770412
- May, C. A., Cipriani, D., & Lorenz, K. A. (2010). Power development through complex training for the division i collegiate athlete. *Strength & Conditioning Journal*, 32(4), 30-43.
- McAndrew, D., Gorelick, M., & Brown, J. (2006). Muscles within muscles: A mechanomyographic analysis of muscle segment contractile properties within human gluteus maximus. *Journal of Musculoskeletal Research*, 10(01), 23-35.
- McBride, J. M., Blow, D., Kirby, T. J., Haines, T. L., Dayne, A. M., & Triplett, N. T. (2009). Relationship between maximal squat strength and five, ten, and forty yard sprint times. *Journal of Strength and Conditioning Research*, 23(6), 1633-1636. doi:10.1519/JSC.0b013e3181b2b8aa

- McBride, J. M., Triplett-McBride, T., Davie, A. J., Abernethy, P. J., & Newton, R. U. (2003). Characteristics of titin in strength and power athletes. *European Journal of Applied Physiology*, 88(6), 553-557. doi:10.1007/s00421-002-0733-y
- McCaw, S. T., & Friday, J. J. (1994). A comparison of muscle activity between a free weight and machine bench press. *The Journal of Strength & Conditioning Research*, 8(4), 259-264.
- McCaw, S. T., & Melrose, D. R. (1999). Stance width and bar load effects on leg muscle activity during the parallel squat. *Medicine and Science in Sports and Exercise*, 31(3), 428-436.
- McGill, S. M. (1990). Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: Implications for lumbar mechanics. *Journal of Orthopaedic Research*, 9(1), 91-103. doi:10.1002/jor.1100090112
- McGill, S. M., & Marshall, L. W. (2012). Kettlebell swing, snatch, and bottoms-up carry: Back and hip muscle activation, motion, and low back loads. *Journal of Strength and Conditioning Research*, 26(1), 16-27. doi:10.1519/JSC.0b013e31823a4063
- McGill, S. M., McDermott, A., & Fenwick, C. M. (2009). Comparison of different strongman events: Trunk muscle activation and lumbar spine motion, load, and stiffness. *Journal of Strength and Conditioning Research*, 23(4), 1148-1161. doi:10.1519/JSC.0b013e318198f8f7
- McKean, M., & Burkett, B. J. (2012). Does segment length influence the hip, knee and ankle coordination during the squat movement? *Journal of Fitness Research*, 1(1), 23-30.
- McLaughlin, M. J., & Sainani, K. L. (2014). Bonferroni, holm, and hochberg corrections: Fun names, serious changes to p values. *PM R*, 6(6), 544-546. doi:10.1016/j.pmrj.2014.04.006
- McMaster, D. T., Cronin, J., & McGuigan, M. (2009). Forms of variable resistance training. *Strength & Conditioning Journal*, 31(1), 50-64.
- McMaster, D. T., Cronin, J., & McGuigan, M. R. (2010). Quantification of rubber and chain-based resistance modes. *Journal of Strength and Conditioning Research*, 24(8), 2056-2064. doi:10.1519/JSC.0b013e3181dc4200
- Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., . . . Mendez-Villanueva, A. (2014). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players. *Scandinavian Journal of Medicine and Science in Sports*. doi:10.1111/sms.12388
- Mero, A. (1988). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise and Sport*, 59(2), 94-98.
- Mero, A., & Komi, P. V. (1994). Emg, force, and power analysis of sprint-specific strength exercises. *Journal of Applied Biomechanics*, 10(1).
- Mohamad, N. I., Cronin, J. B., & Nosaka, K. K. (2012). The effect of aerobic exercise during the interset rest periods on kinematics, kinetics, and lactate clearance of two resistance loading schemes. *Journal of Strength and Conditioning Research*, 26(1), 73-79. doi:10.1519/JSC.0b013e31821bflf5
- Mohamed, O., Perry, J., & Hislop, H. (2002). Relationship between wire emg activity, muscle length, and torque of the hamstrings. *Clinical Biomechanics (Bristol, Avon)*, 17(8), 569-579.
- Moir, G. L., Graham, B. W., Davis, S. E., Guers, J. J., & Witmer, C. A. (2013). Effect of cluster set configurations on mechanical variables during the deadlift exercise. *Journal of Human Kinetics*, 39, 15-23. doi:10.2478/hukin-2013-0064

- Moir, G. L., Mergy, D., Witmer, C., & Davis, S. E. (2011). The acute effects of manipulating volume and load of back squats on countermovement vertical jump performance. *Journal of Strength and Conditioning Research*, 25(6), 1486-1491. doi:10.1519/JSC.0b013e3181da8597
- Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, 112(11), 3921-3930. doi:10.1007/s00421-012-2379-8
- Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine and Science in Sports and Exercise*, 43(9), 1680-1688. doi:10.1249/MSS.0b013e318216ea37
- Morrissey, M. C., Harman, E. A., Frykman, P. N., & Han, K. H. (1998). Early phase differential effects of slow and fast barbell squat training. *American Journal of Sports Medicine*, 26(2), 221-230.
- Morrissey, M. C., Harman, E. A., & Johnson, M. J. (1995). Resistance training modes: Specificity and effectiveness. *Medicine and Science in Sports and Exercise*, 27(5), 648-660.
- Munro, C. F., Miller, D. I., & Fuglevand, A. J. (1987). Ground reaction forces in running: A reexamination. *Journal of Biomechanics*, 20(2), 147-155.
- Nagano, A., Komura, T., & Fukashiro, S. (2007). Optimal coordination of maximal-effort horizontal and vertical jump motions--a computer simulation study. *BioMedical Engineering OnLine*, 6, 20. doi:10.1186/1475-925X-6-20
- Neumann, D. A. (2010). Kinesiology of the hip: A focus on muscular actions. *Journal of Orthopaedic and Sports Physical Therapy*, 40(2), 82-94. doi:10.2519/jospt.2010.3025
- Nishikawa, K. C., Monroy, J. A., Uyeno, T. E., Yeo, S. H., Pai, D. K., & Lindstedt, S. L. (2012). Is titin a 'winding filament'? A new twist on muscle contraction. *Proceedings: Biological Sciences*, 279(1730), 981-990. doi:10.1098/rspb.2011.1304
- Noe, D. A., Mostardi, R. A., Jackson, M. E., Porterfield, J. A., & Askew, M. J. (1992). Myoelectric activity and sequencing of selected trunk muscles during isokinetic lifting. *Spine*, 17(2), 225-229.
- Nourbakhsh, M. R., & Ottenbacher, K. J. (1994). The statistical analysis of single-subject data: A comparative examination. *Physical Therapy*, 74(8), 768-776.
- Nummela, A., Rusko, H., & Mero, A. (1994). Emg activities and ground reaction forces during fatigued and nonfatigued sprinting. *Medicine and Science in Sports and Exercise*, 26(5), 605-609.
- Oh, J. S., Cynn, H. S., Won, J. H., Kwon, O. Y., & Yi, C. H. (2007). Effects of performing an abdominal drawing-in maneuver during prone hip extension exercises on hip and back extensor muscle activity and amount of anterior pelvic tilt. *Journal of Orthopaedic and Sports Physical Therapy*, 37(6), 320-324. doi:10.2519/jospt.2007.2435
- Oliver, G. D., & Dougherty, C. P. (2009). Comparison of hamstring and gluteus muscles electromyographic activity while performing the razor curl vs. The traditional prone hamstring curl. *Journal of Strength and Conditioning Research*, 23(8), 2250-2255. doi:10.1519/JSC.0b013e3181b8d34b
- Otto, W. H., 3rd, Coburn, J. W., Brown, L. E., & Spiering, B. A. (2012). Effects of weightlifting vs. Kettlebell training on vertical jump, strength, and body composition. *Journal of Strength and Conditioning Research*, 26(5), 1199-1202. doi:10.1519/JSC.0b013e31824f233e
- Pandy, M. G., & Zajac, F. E. (1991). Optimal muscular coordination strategies for jumping. *Journal of Biomechanics*, 24(1), 1-10.

- Paoli, A., Marcolin, G., & Petrone, N. (2008). The effect of stance width on the electromyographical activity of eight superficial thigh muscles during back squat with different bar loads. *Journal of Strength and Conditioning Research*, 23(1), 246-250.
- Paoli, A., Marcolin, G., & Petrone, N. (2009). The effect of stance width on the electromyographical activity of eight superficial thigh muscles during back squat with different bar loads. *Journal of Strength and Conditioning Research*, 23(1), 246-250.
- Park, S. Y., & Yoo, W. G. (2014). Effects of hand and knee positions on muscular activity during trunk extension exercise with the roman chair. *Journal of Electromyography and Kinesiology*, 24(6), 972-976. doi:10.1016/j.jelekin.2014.08.012
- Pearson, S. N., Cronin, J. B., Hume, P. A., & Slyfield, D. (2009). Kinematics and kinetics of the bench-press and bench-pull exercises in a strength-trained sporting population. *Sports Biomechanics*, 8(3), 245-254. doi:10.1080/14763140903229484
- Perdices, M., & Tate, R. L. (2009). Single-subject designs as a tool for evidence-based clinical practice: Are they unrecognised and undervalued? *Neuropsychological Rehabilitation*, 19(6), 904-927. doi:10.1080/09602010903040691
- Pierce, K. (1997). Basic back squat. *Strength & Conditioning Journal*, 19(2), 20-21.
- Popov, D. V., Tsvirkun, D. V., Netreba, A. I., Tarasova, O. S., Prostova, A. B., Larina, I. M., . . . Vinogradova, O. L. (2006). [hormonal adaptation determines the increase in muscle mass and strength during low-intensity strength training without relaxation]. *Fiziologiya Cheloveka*, 32(5), 121-127.
- Queiroz, B. C., Cagliari, M. F., Amorim, C. F., & Sacco, I. C. (2010). Muscle activation during four pilates core stability exercises in quadruped position. *Archives of Physical Medicine and Rehabilitation*, 91(1), 86-92. doi:10.1016/j.apmr.2009.09.016
- Rabita, G., Dorel, S., Slawinski, J., Saez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J. B. (2015). Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scandinavian Journal of Medicine and Science in Sports*. doi:10.1111/sms.12389
- Raez, M. B., Hussain, M. S., & Mohd-Yasin, F. (2006). Techniques of emg signal analysis: Detection, processing, classification and applications. *Biological Procedures Online*, 8, 11-35. doi:10.1251/bpo115
- Ramirez-Campillo, R., Gallardo, F., Henriquez-Olguin, C., Meylan, C., Martinez, C., Alvarez, C., . . . Izquierdo, M. (2014). Effect of vertical, horizontal and combined plyometric training on explosive, balance and endurance performance of young soccer players. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000000827
- Randell, A. D. (2011). *Optimising transference of strength and power adaptation to sports specific performance*. Auckland University of Technology.
- Randell, A. D., Cronin, J. B., Keogh, J. W., & Gill, N. D. (2010). Transference of strength and power adaptation to sports performance—horizontal and vertical force production. *Strength & Conditioning Journal*, 32(4), 100-106.
- Reiman, M. P., Bolgla, L. A., & Loudon, J. K. (2012). A literature review of studies evaluating gluteus maximus and gluteus medius activation during rehabilitation exercises. *Physiotherapy Theory and Practice*, 28(4), 257-268. doi:10.3109/09593985.2011.604981
- Renshaw, D., Bice, M. R., Cassidy, C., Eldridge, J. A., Powell, & Douglas, W. (2010). A comparison of three computer-based methods used to determine emg signal amplitude. *International Journal of Exercise Science*, 3(1), 1-7.

- Requena, B., Garcia, I., Requena, F., de Villarreal, E. S., & Cronin, J. B. (2011). Relationship between traditional and ballistic squat exercise with vertical jumping and maximal sprinting. *Journal of Strength and Conditioning Research*, 25(8), 2193-2204. doi:10.1519/JSC.0b013e3181e86132
- Rhea, M. R., Kenn, J. G., & Dermody, B. M. (2009). Alterations in speed of squat movement and the use of accommodated resistance among college athletes training for power. *Journal of Strength and Conditioning Research*, 23(9), 2645-2650. doi:10.1519/JSC.0b013e3181b3e1b6
- Robertson, D. G., Wilson, J. M., & St Pierre, T. A. (2008). Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics*, 24(4), 333-339.
- Roundtable, C. (1984). Speed development. *NSCA J*, 5(6), 12-20.
- Rowe, J., Shafer, L., Kelley, K., West, N., Dunning, T., Smith, R., & Mattson, D. J. (2007). Hip strength and knee pain in females. *North American journal of sports physical therapy : NAJSPT*, 2(3), 164-169.
- Russell, P. J., & Phillips, S. J. (1989). A preliminary comparison of front and back squat exercises. *Research Quarterly for Exercise and Sport*, 60(3), 201-208. doi:10.1080/02701367.1989.10607441
- Saeterbakken, A. H., Andersen, V., Kolnes, M. K., & Fimland, M. S. (2014). Effects of replacing free weights with elastic band resistance in squats on trunk muscle activation. *Journal of Strength and Conditioning Research*, 28(11), 3056-3062. doi:10.1519/JSC.0000000000000516
- Sakamaki, M., Bemben, M. G., & Abe, T. (2011). Legs and trunk muscle hypertrophy following walk training with restricted leg muscle blood flow. *Journal of Sports Science & Medicine*, 10(2), 338-340.
- Sakamoto, A. C., Teixeira-Salmela, L. F., de Paula-Goulart, F. R., de Moraes Faria, C. D., & Guimaraes, C. Q. (2009). Muscular activation patterns during active prone hip extension exercises. *Journal of Electromyography and Kinesiology*, 19(1), 105-112. doi:10.1016/j.jelekin.2007.07.004
- Sale, D. G. (1988). Neural adaptation to resistance training. *Medicine and Science in Sports and Exercise*, 20(5 Suppl), S135-145.
- Schache, A. G., Blanch, P. D., Dorn, T. W., Brown, N. A., Rosemond, D., & Pandy, M. G. (2011). Effect of running speed on lower limb joint kinetics. *Medicine and Science in Sports and Exercise*, 43(7), 1260-1271. doi:10.1249/MSS.0b013e3182084929
- Schache, A. G., Kim, H. J., Morgan, D. L., & Pandy, M. G. (2010). Hamstring muscle forces prior to and immediately following an acute sprinting-related muscle strain injury. *Gait and Posture*, 32(1), 136-140. doi:10.1016/j.gaitpost.2010.03.006
- Schaub, P. A., & Worrell, T. W. (1995). Emg activity of six muscles and vmo: VL ratio determination during a maximal squat exercise. *Journal of Sport Rehabilitation*, 4, 195-202.
- Schoenfeld, B. J. (2010a). The mechanisms of muscle hypertrophy and their application to resistance training. *Journal of Strength and Conditioning Research*, 24(10), 2857-2872. doi:10.1519/JSC.0b013e3181e840f3
- Schoenfeld, B. J. (2010b). Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength and Conditioning Research*, 24(12), 3497-3506. doi:10.1519/JSC.0b013e3181bac2d7
- Schoenfeld, B. J. (2012). Does exercise-induced muscle damage play a role in skeletal muscle hypertrophy? *Journal of Strength and Conditioning Research*, 26(5), 1441-1453. doi:10.1519/JSC.0b013e31824f207e
- Schoenfeld, B. J., Contreras, B., Tiryaki-Sonmez, G., Willardson, J. M., & Fontana, F. (2014). An electromyographic comparison of a modified version of the plank

- with a long lever and posterior tilt versus the traditional plank exercise. *Sports Biomechanics*, 13(3), 296-306. doi:10.1080/14763141.2014.942355
- Schoenfeld, B. J., Contreras, B., Willardson, J. M., Fontana, F., & Tiryaki-Sonmez, G. (2014). Muscle activation during low- versus high-load resistance training in well-trained men. *European Journal of Applied Physiology*, 114(12), 2491-2497. doi:10.1007/s00421-014-2976-9
- Schoenfeld, B. J., Ratamess, N. A., Peterson, M. D., Contreras, B., Sonmez, G. T., & Alvar, B. A. (2014). Effects of different volume-equated resistance training loading strategies on muscular adaptations in well-trained men. *Journal of Strength and Conditioning Research*, 28(10), 2909-2918. doi:10.1519/JSC.0000000000000480
- Schuenke, M. D., Herman, J. R., Gliders, R. M., Hagerman, F. C., Hikida, R. S., Rana, S. R., . . . Staron, R. S. (2012). Early-phase muscular adaptations in response to slow-speed versus traditional resistance-training regimens. *European Journal of Applied Physiology*, 112(10), 3585-3595. doi:10.1007/s00421-012-2339-3
- Schwanbeck, S., Chilibeck, P. D., & Binsted, G. (2009). A comparison of free weight squat to smith machine squat using electromyography. *Journal of Strength and Conditioning Research*, 23(9), 2588-2591. doi:10.1519/JSC.0b013e3181b1b181
- Seitz, L. B., Reyes, A., Tran, T. T., de Villarreal, E. S., & Haff, G. G. (2014). Increases in lower-body strength transfer positively to sprint performance: A systematic review with meta-analysis. *Sports Medicine*. doi:10.1007/s40279-014-0227-1
- Selkowitz, D. M., Beneck, G. J., & Powers, C. M. (2013). Which exercises target the gluteal muscles while minimizing activation of the tensor fascia lata? Electromyographic assessment using fine-wire electrodes. *Journal of Orthopaedic and Sports Physical Therapy*, 43(2), 54-64. doi:10.2519/jospt.2013.4116
- Shaner, A. A., Vingren, J. L., Hatfield, D. L., Budnar, R. G., Jr., Duplanty, A. A., & Hill, D. W. (2014). The acute hormonal response to free weight and machine weight resistance exercise. *Journal of Strength and Conditioning Research*, 28(4), 1032-1040. doi:10.1519/JSC.0000000000000317
- Shimokochi, Y., Ide, D., Kokubu, M., & Nakaoji, T. (2013). Relationships among performance of lateral cutting maneuver from lateral sliding and hip extension and abduction motions, ground reaction force, and body center of mass height. *Journal of Strength and Conditioning Research*, 27(7), 1851-1860. doi:10.1519/JSC.0b013e3182764945
- Siff, M. C. (2003). *Supertraining*: Supertraining Institute.
- Simenz, C. J., Dugan, C. A., & Ebben, W. P. (2005). Strength and conditioning practices of national basketball association strength and conditioning coaches. *Journal of Strength and Conditioning Research*, 19(3), 495-504. doi:10.1519/15264.1
- Simenz, C. J., Garceau, L. R., Lutsch, B. N., Suchomel, T. J., & Ebben, W. P. (2012). Electromyographical analysis of lower extremity muscle activation during variations of the loaded step-up exercise. *Journal of Strength and Conditioning Research*, 26(12), 3398-3405. doi:10.1519/JSC.0b013e3182472fad
- Singh, D., & Singh, S. (2012). Effects of vertical, horizontal, and combination depth jump training on long jump performance. *Biomedical Human Kinetics*, 4, 107-111.
- Singh, D., & Singh, S. (2013). Effects of vertical and horizontal plyometric exercises on running speed. *Human movement*, 14(2), 144-147.
- Sizonenko, P. C. (1978). Endocrinology in preadolescents and adolescents. I. Hormonal changes during normal puberty. *American Journal of Diseases of Children*, 132(7), 704-712.

- Souza, A. L., Shimada, S. D., & Koontz, A. (2002). Ground reaction forces during the power clean. *Journal of Strength and Conditioning Research*, 16(3), 423-427.
- Souza, R. B., & Powers, C. M. (2009). Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *Journal of Orthopaedic and Sports Physical Therapy*, 39(1), 12-19. doi:10.2519/jospt.2009.2885
- Speirs, D. E., Bennett, M., Finn, C. V., & Turner, A. P. (2015). Unilateral vs bilateral squat training for strength, sprints and agility in academy rugby players. *Journal of Strength and Conditioning Research*. doi:10.1519/JSC.0000000000001096
- Spinks, C. D., Murphy, A. J., Spinks, W. L., & Lockie, R. G. (2007). The effects of resisted sprint training on acceleration performance and kinematics in soccer, rugby union, and Australian football players. *Journal of Strength and Conditioning Research*, 21(1), 77-85. doi:10.1519/R-18145.1
- Stensdotter, A. K., Hodges, P. W., Mellor, R., Sundelin, G., & Hager-Ross, C. (2003). Quadriceps activation in closed and in open kinetic chain exercise. *Medicine and Science in Sports and Exercise*, 35(12), 2043-2047. doi:10.1249/01.MSS.0000099107.03704.AE
- Stuart, M. J., Meglan, D. A., Lutz, G. E., Growney, E. S., & An, K. N. (1996). Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. *American Journal of Sports Medicine*, 24(6), 792-799.
- Suehiro, T., Mizutani, M., Okamoto, M., Ishida, H., Kobara, K., Fujita, D., . . . Watanabe, S. (2014). Influence of hip joint position on muscle activity during prone hip extension with knee flexion. *Journal of Physical Therapy Science*, 26(12), 1895-1898. doi:10.1589/jpts.26.1895
- Sundstrup, E., Jakobsen, M. D., Andersen, C. H., Bandholm, T., Thorborg, K., Zebis, M. K., & Andersen, L. L. (2014). Evaluation of elastic bands for lower extremity resistance training in adults with and without musculo-skeletal pain. *Scandinavian Journal of Medicine and Science in Sports*, 24(5), e353-359. doi:10.1111/sms.12187
- Sundstrup, E., Jakobsen, M. D., Andersen, C. H., Zebis, M. K., Mortensen, O. S., & Andersen, L. L. (2012). Muscle activation strategies during strength training with heavy loading vs. Repetitions to failure. *Journal of Strength and Conditioning Research*, 26(7), 1897-1903. doi:10.1519/JSC.0b013e318239c38e
- Swinton, P. A., Lloyd, R., Keogh, J. W., Agouris, I., & Stewart, A. D. (2012). A biomechanical comparison of the traditional squat, powerlifting squat, and box squat. *Journal of Strength and Conditioning Research*, 26(7), 1805-1816. doi:10.1519/JSC.0b013e3182577067
- Swinton, P. A., Stewart, A., Agouris, I., Keogh, J. W., & Lloyd, R. (2011). A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads. *Journal of Strength and Conditioning Research*, 25(7), 2000-2009. doi:10.1519/JSC.0b013e3181e73f87
- Swinton, P. A., Stewart, A. D., Keogh, J. W., Agouris, I., & Lloyd, R. (2011). Kinematic and kinetic analysis of maximal velocity deadlifts performed with and without the inclusion of chain resistance. *Journal of Strength and Conditioning Research*, 25(11), 3163-3174. doi:10.1519/JSC.0b013e318212e389
- Swinton, P. A., Stewart, A. D., Lloyd, R., Agouris, I., & Keogh, J. W. (2012). Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. *Journal of Strength and Conditioning Research*, 26(4), 906-913. doi:10.1519/JSC.0b013e31822e589e

- Taniguchi, M., Fukumoto, Y., Kobayashi, M., Kawasaki, T., Maegawa, S., Ibuki, S., & Ichihashi, N. (2015). Quantity and quality of the lower extremity muscles in women with knee osteoarthritis. *Ultrasound in Medicine and Biology*. doi:10.1016/j.ultrasmedbio.2015.05.014
- Tanimoto, M., Sanada, K., Yamamoto, K., Kawano, H., Gando, Y., Tabata, I., . . . Miyachi, M. (2008). Effects of whole-body low-intensity resistance training with slow movement and tonic force generation on muscular size and strength in young men. *Journal of Strength and Conditioning Research*, 22(6), 1926-1938. doi:10.1519/JSC.0b013e318185f2b0
- Tateuchi, H., Taniguchi, M., Mori, N., & Ichihashi, N. (2012). Balance of hip and trunk muscle activity is associated with increased anterior pelvic tilt during prone hip extension. *Journal of Electromyography and Kinesiology*, 22(3), 391-397. doi:10.1016/j.jelekin.2012.03.003
- Tateuchi, H., Tsukagoshi, R., Fukumoto, Y., Akiyama, H., So, K., Kuroda, Y., & Ichihashi, N. (2013). Pelvic instability and trunk and hip muscle recruitment patterns in patients with total hip arthroplasty. *Journal of Electromyography and Kinesiology*, 23(1), 151-158. doi:10.1016/j.jelekin.2012.08.005
- Thalacker-Mercer, A., Stec, M., Cui, X., Cross, J., Windham, S., & Bamman, M. (2013). Cluster analysis reveals differential transcript profiles associated with resistance training-induced human skeletal muscle hypertrophy. *Physiological Genomics*, 45(12), 499-507. doi:10.1152/physiolgenomics.00167.2012
- Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L., . . . Heiderscheit, B. C. (2004). Hamstring muscle kinematics during treadmill sprinting. *Medicine and Science in Sports and Exercise*, 37(1), 108-114. doi:10.1249/01.MSS.0000150078.79120.C8
- Thomasian, B. C. (2015). The effect of vertically-and horizontally-directed plyometric exercise on sprint running performance.
- Timmons, J. A. (2011). Variability in training-induced skeletal muscle adaptation. *Journal of Applied Physiology*, 110(3), 846-853. doi:10.1152/japplphysiol.00934.2010
- Tricoli, V., Lamas, L., Carnevale, R., & Ugrinowitsch, C. (2005). Short-term effects on lower-body functional power development: Weightlifting vs. Vertical jump training programs. *Journal of Strength and Conditioning Research*, 19(2), 433-437. doi:10.1519/R-14083.1
- Turner, A. N., Cree, J., Comfort, P., Jones, L., Chavda, S., Bishop, C., & Reynolds, A. (2014). Hamstring strain prevention in elite soccer players. *Strength & Conditioning Journal*, 36(5), 10-20.
- Vakos, J. P., Nitz, A. J., Threlkeld, A. J., Shapiro, R., & Horn, T. (1994). Electromyographic activity of selected trunk and hip muscles during a squat lift. Effect of varying the lumbar posture. *Spine*, 19(6), 687-695.
- Van Dillen, L. R., McDonnell, M. K., Fleming, D. A., & Sahrman, S. A. (2000). Effect of knee and hip position on hip extension range of motion in individuals with and without low back pain. *Journal of Orthopaedic and Sports Physical Therapy*, 30(6), 307-316. doi:10.2519/jospt.2000.30.6.307
- Vangelder, L. H., Hoogenboom, B. J., & Vaughn, D. W. (2013). A phased rehabilitation protocol for athletes with lumbar intervertebral disc herniation. *International Journal of Sports Physical Therapy*, 8(4), 482-516.
- Vera-Garcia, F. J., Moreside, J. M., & McGill, S. M. (2010). Mvc techniques to normalize trunk muscle emg in healthy women. *Journal of Electromyography and Kinesiology*, 20(1), 10-16. doi:10.1016/j.jelekin.2009.03.010

- Vigotsky, A. D., Harper, E. N., Ryan, D. R., & Contreras, B. (2015). Effects of load on good morning kinematics and emg activity. *PeerJ*, 3, e708. doi:10.7717/peerj.708
- Wagner, T., Behnia, N., Ancheta, W. K., Shen, R., Farrokhi, S., & Powers, C. M. (2010). Strengthening and neuromuscular reeducation of the gluteus maximus in a triathlete with exercise-associated cramping of the hamstrings. *Journal of Orthopaedic and Sports Physical Therapy*, 40(2), 112-119. doi:10.2519/jospt.2010.3110
- Wakahara, T., Fukutani, A., Kawakami, Y., & Yanai, T. (2013). Nonuniform muscle hypertrophy: Its relation to muscle activation in training session. *Medicine and Science in Sports and Exercise*, 45(11), 2158-2165. doi:10.1249/MSS.0b013e3182995349
- Wakahara, T., Miyamoto, N., Sugisaki, N., Murata, K., Kanehisa, H., Kawakami, Y., . . . Yanai, T. (2012). Association between regional differences in muscle activation in one session of resistance exercise and in muscle hypertrophy after resistance training. *European Journal of Applied Physiology*, 112(4), 1569-1576. doi:10.1007/s00421-011-2121-y
- Wallace, B. J., Winchester, J. B., & McGuigan, M. R. (2006). Effects of elastic bands on force and power characteristics during the back squat exercise. *Journal of Strength and Conditioning Research*, 20(2), 268-272. doi:10.1519/R-16854.1
- Waller, M. A., Gersick, M. J., Townsend, R. J., & Ford, C. N. (2014). Strength and conditioning preparation for the transitional track and field thrower. *Strength & Conditioning Journal*, 36(6), 71-78.
- Walmsley, R. P., & Amell, T. K. (1996). The application and interpretation of intraclass correlations in the assessment of reliability in isokinetic dynamometry. *Isokinetics and Exercise Science*, 2(6), 117-124.
- Ward, S. R., Eng, C. M., Smallwood, L. H., & Lieber, R. L. (2009). Are current measurements of lower extremity muscle architecture accurate? *Clinical Orthopaedics and Related Research*, 467(4), 1074-1082. doi:10.1007/s11999-008-0594-8
- Waryasz, G. R. (2010). Exercise strategies to prevent the development of the anterior pelvic tilt: Implications for possible prevention of sports hernias and osteitis pubis. *Strength & Conditioning Journal*, 32(4), 56-65.
- Weber, K. R., Brown, L. E., Coburn, J. W., & Zinder, S. M. (2008). Acute effects of heavy-load squats on consecutive squat jump performance. *Journal of Strength and Conditioning Research*, 22(3), 726-730. doi:10.1519/JSC.0b013e3181660899
- Weber-Lehmann, J., Schilling, E., Gradl, G., Richter, D. C., Wiehler, J., & Rolf, B. (2014). Finding the needle in the haystack: Differentiating "identical" twins in paternity testing and forensics by ultra-deep next generation sequencing. *Forensic Sci Int Genet*, 9, 42-46. doi:10.1016/j.fsigen.2013.10.015
- Wheatley, M. D., & Jahnke, W. D. (1951). Electromyographic study of the superficial thigh and hip muscles in normal individuals. *Archives of Physical Medicine and Rehabilitation*, 32(8), 508-515.
- Wilk, K. E., Escamilla, R. F., Fleisig, G. S., Barrentine, S. W., Andrews, J. R., & Boyd, M. L. (1996). A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *American Journal of Sports Medicine*, 24(4), 518-527.
- Wilson, G. J., Murphy, A. J., & Walshe, A. (1996). The specificity of strength training: The effect of posture. *European Journal of Applied Physiology and Occupational Physiology*, 73(3-4), 346-352.

- Wilson, J., Ferris, E., Heckler, A., Maitland, L., & Taylor, C. (2005). A structured review of the role of gluteus maximus in rehabilitation. *New Zealand Journal of Physiotherapy*, 33(3), 95-100.
- Winter, E. M. (2005). Jumping: Power or impulse? *Medicine and Science in Sports and Exercise*(37), 523.
- Wisloff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine*, 38(3), 285-288.
- Witmer, C. A., Davis, S. E., & Moir, G. L. (2010). The acute effects of back squats on vertical jump performance in men and women. *Journal of Sports Science & Medicine*, 9(2), 206-213.
- Worrell, T. W., Karst, G., Adamczyk, D., Moore, R., Stanley, C., Steimel, B., & Steimel, S. (2001). Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. *Journal of Orthopaedic and Sports Physical Therapy*, 31(12), 730-740. doi:10.2519/jospt.2001.31.12.730
- Wretenberg, P., Feng, Y., & Arborelius, U. P. (1996). High- and low-bar squatting techniques during weight-training. *Medicine and Science in Sports and Exercise*, 28(2), 218-224.
- Wu, W.-L., Wu, J.-H., Lin, H.-T., & Wang, G.-J. (2003). Biomechanical analysis of the standing long jump. *Biomedical Engineering: Applications, Basis and Communications*, 15(05), 186-192.
- Yamashita, N. (1988). Emg activities in mono- and bi-articular thigh muscles in combined hip and knee extension. *European Journal of Applied Physiology and Occupational Physiology*, 58(3), 274-277.
- Yasuda, T., Fukumura, K., Fukuda, T., Uchida, Y., Iida, H., Meguro, M., . . . Nakajima, T. (2014). Muscle size and arterial stiffness after blood flow-restricted low-intensity resistance training in older adults. *Scandinavian Journal of Medicine and Science in Sports*, 24(5), 799-806. doi:10.1111/sms.12087
- Yavuz, H. U., Erdag, D., Amca, A. M., & Aritan, S. (2015). Kinematic and emg activities during front and back squat variations in maximum loads. *Journal of Sports Sciences*, 33(10), 1058-1066. doi:10.1080/02640414.2014.984240
- Yetter, M., & Moir, G. L. (2008). The acute effects of heavy back and front squats on speed during forty-meter sprint trials. *Journal of Strength and Conditioning Research*, 22(1), 159-165. doi:10.1519/JSC.0b013e31815f958d
- Youdas, J. W., Adams, K. E., Bertucci, J. E., Brooks, K. J., Nelson, M. M., & Hollman, J. H. (2014). Muscle activation levels of the gluteus maximus and medius during standing hip-joint strengthening exercises using elastic-tubing resistance. *Journal of Sport Rehabilitation*, 23(1), 1-11. doi:10.1123/jsr.2012-0082
- Youdas, J. W., Foley, B. M., Kruger, B. L., Mangus, J. M., Tortorelli, A. M., Madson, T. J., & Hollman, J. H. (2013). Electromyographic analysis of trunk and hip muscles during resisted lateral band walking. *Physiotherapy Theory and Practice*, 29(2), 113-123. doi:10.3109/09593985.2012.704492

APPENDICES

Appendix 1. Ethics Approval Forms

Appendix 1a. Ethics Application Number 13/375



16 December 2013

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **13/375 Electromyographical activity of various hip extension exercises.**

Thank you for providing evidence as requested, which satisfies the points raised by the AUT University Ethics Committee (AUTC).

Your ethics application has been approved for three years until 16 December 2016.

As part of the ethics approval process, you are required to submit the following to AUTC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 16 December 2016;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 16 December 2016 or on completion of the project.

It is a condition of approval that AUTC is notified of any adverse events or if the research does not commence.

AUTC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee
Cc: Bret Contreras bretcontreras@hotmail.com

Appendix 1b. Ethics Application Number 14/267



A U T E C
S E C R E T A R I A T

25 September 2014

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **14/267 Kinematic, Kinetic and morphological adaptations to training with various hip extension exercises.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 25 September 2017.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through <http://www.aut.ac.nz/researchethics>. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 25 September 2017;
- A brief report on the status of the project using form EA3, which is available online through <http://www.aut.ac.nz/researchethics>. This report is to be submitted either when the approval expires on 25 September 2017 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence.

AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.


To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee
Cc: Bret Contreras bretcontreras@hotmail.com

Appendix 2. Consent Forms

Appendix 2a. Electromyographical Activity of Various Hip Extension Exercises

<i>Internal Mail Code: RC</i> <i>Consent Form</i>	 AUT UNIVERSITY <small>TE WĀNANGA ARONUI O TAMAKI MAKAU RAU</small>
--	--

Project title: Electromyographical activity of various hip extension exercises

Project Supervisor: **John Cronin**

Researcher: **Bret Contreras**

- ☐ I have read and understood the information provided about this research project in the Information Sheet dated dd mmmm yyyy.
- ☐ I have had an opportunity to ask questions and to have them answered.
- ☐ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ☐ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection.
- ☐ I agree to provide EMG and anthropometric data.
- ☐ I realize that my contact details (and data) will be stored indefinitely in the SPRINZ research database in case I need to be contacted for possible follow up research.
- ☐ I agree to take part in this research.
- ☐ I wish to receive a copy of the report from the research (please tick one): Yes ☐ No ☐
- ☐ I wish to have my EMG data returned to me in accordance with right 7 (9) of the *Code of Health and Disability Services Consumers' Rights* (please tick one): Yes ☐ No ☐

Participant's signature:

.....

Participant's name:

.....

Participant's Contact Details (if appropriate):

.....


.....
.....
.....

Date:

Approved by the Auckland University of Technology Ethics Committee on 16 Dec 2013, AUTEK Reference number 13/375

Note: The Participant should retain a copy of this form.

Appendix 2b. Kinematic, Kinetic and Morphological Adaptations to Training with Various Hip Extension Exercises

<i>Internal Mail Code: RC</i> <i>Consent Form</i>	 AUT UNIVERSITY <small>TE WĀNANGA ARONUI O TAMAKI MAKAU RAU</small>
--	--

Project title: Kinematic, Kinetic and Morphological Adaptations to Training with Various Hip Extension Exercises

Project Supervisor: **John Cronin**

Researcher: **Bret Contreras**

- ☐ I have read and understood the information provided about this research project in the Information Sheet dated 27 April 2015.
- ☐ I have had an opportunity to ask questions and to have them answered.
- ☐ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ☐ I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance, or any infection.
- ☐ I agree to provide anthropometric, kinematic, kinetic, and morphological data.
- ☐ I realize that my contact details (and data) will be stored indefinitely in the SPRINZ research database in case I need to be contacted for possible follow up research.
- ☐ I agree to take part in this research.
- ☐ I wish to receive a copy of the report from the research (please tick one): Yes ☐ No ☐
- ☐ I understand that resistance training involves inherent risks and I agree to hold harmless Bret Contreras, BC Athletics LLC, St. Kents, and AUT University
- ☐ I certify that I currently have medical insurance and I assume responsibility for any medical costs relating to any incident or injury incurred during or because of the resistance training provided to me

Participant's signature:

.....

Participant's name:

.....

Participant's Contact Details (if appropriate):

.....
.....

.....
.....
Date:

*Approved by the Auckland University of Technology Ethics Committee on 25 Sept
2014 AUTEC Reference number 14267_04092014*

Note: The Participant should retain a copy of this form.

Appendix 2c. Kinematic, Kinetic and Morphological Adaptations to Training With Various Hip Extension Exercises

Assent Form

For completion by legal minors (people aged under 16 years). This must be accompanied by a Consent Form. When pre-schoolers are involved, please use the special Children's Information Sheet in the Ethics Knowledge Base.



Project title: Kinematic, Kinetic and Morphological Adaptations to Training with Various Hip Extension Exercises

Project Supervisor: ***John Cronin***

Researcher: ***Bret Contreras***

- ☐ I have read and understood the sheet telling me what will happen in this study and why it is important.
- ☐ I have been able to ask questions and to have them answered.
- ☐ I understand that while the information is being collected, I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.
- ☐ If I stop being part of the study, I understand that all information about me, including the recordings or any part of them that include me, will be destroyed.
- ☐ I agree to take part in this research.

Participant's

signature:

Participant's

name:

Participant's Contact Details (if appropriate):

.....
.....
.....
.....

Date:

Approved by the Auckland University of Technology Ethics Committee on 25 Sept 2014 AUTEK Reference number 14267_04092014

Note: The Participant should retain a copy of this form.

Appendix 3. Study Information Sheets

Appendix 3a. Electromyographical Activity of Various Hip Extension Exercises

Participant Information Sheet



Date Information Sheet Produced:

22 November 2013

Project Title

Electromyographical activity of various hip extension exercises

An Invitation

Hello! My name is Bret Contreras and I am currently seeking my PhD in Sports Science from AUT University. I will be looking at the transfer of various hip strengthening exercise to sports performance and learning a great deal about the squat and hip thrust exercises. I am seeking volunteers to participate in my research project and I hope that you choose to accept my invitation. Please be aware that your participation is completely voluntary and you can withdrawal from data collection at any point in time prior to completion. If you decide not to accept my invitation, I completely understand and appreciate you taking the time to read and consider this invitation.

What is the purpose of this research?

The purpose of this research is to obtain electromyographic (EMG) data, which will inform my culminating training study for my PhD thesis. EMG simply quantifies the amount of electrical activity that a muscle is producing during certain movements and is painless and non-invasive. In particular, I would like to determine: 1) the maximum voluntary contraction (MVC) position that elicits the greatest gluteus maximus EMG activation; 2) the mean and peak gluteus maximus, vastus lateralis, and biceps femoris EMG of the back squat and barbell hip thrust exercises; 3) the influence of squat depth on gluteus maximus EMG activity with identical relative loading; and, 4) the gluteus maximus EMG activity of three different hip thrust variations.

How was I identified and why am I being invited to participate in this research?

You were identified because you responded to a request from my blog seeking volunteers for my research. You indicated that you were between 20-40 years of age and had at least three years of strength training experience.

What will happen in this research?

You will be prepared for the study by having your skin shaven and cleaned prior to having adhesive electrodes attached to the muscles of interest. Thereafter you will perform a number of MVC's in several different positions and different variations of the back squat and barbell hip thrust exercise while these electrodes and associated hardware/software quantify the amount of electrical activity associated with these movements. The muscles of interest are the gluteus maximus, hamstrings and quadriceps musculature during these exercises.

What are the discomforts and risks?

Being hooked up to electrodes is a bit awkward and unnatural. This is especially true for the gluteus maximus region, which requires an electrode to be secured on the buttocks region. The skin under the electrodes will need to be shaved if hair is present which can be awkward and uncomfortable. The electrodes will be secured while you lift weights, which is also a bit unnatural. Lifting weights always involves risk of injury, no matter how careful you are, however, to mitigate this we wish to only include subjects with considerable weight training experience. Steps will be taken to ease your comfort and safety, throughout the study.

How will these discomforts and risks be alleviated?

I will ask permission to palpate and attach electrodes to the muscles of interest. I will use Velcro straps to help secure the electrodes so they stay in position throughout the experiments. You can wear shorts or Spandex over the gluteus maximus electrode, and I will provide you with a proper warm-up and exercise instruction to minimize the risk of injury.

What are the benefits?

Identifying an MVC position for the gluteus maximus will allow researchers to be consistent in their data collection so that better comparisons can be made between gluteus maximus studies. Determining the EMG activity in the various muscles during back squats and barbell hip thrusts will allow coaches, trainers, and athletes to make better programming and training decisions for the purposes of glute development, thigh development, strength, power, speed, and injury prevention.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from your health insurance company. Please check and make sure that you have insurance prior to participating in this study.

How will my privacy be protected?

Your name will be kept confidential. All data is de-identified and the results are either presented as grouped data or referred to as "subject #1," "subject #2," etc. Your personal results can be returned to you on request. What you choose to do with the data is your decision, but I request that it not be released into the public domain until after the data has been published in a peer-reviewed journal.

What are the costs of participating in this research?

There are no financial costs associated with this research, however, 2-4 hours of your time will be needed.

What opportunity do I have to consider this invitation?

Please let me know within a week if you accept this invitation.

How do I agree to participate in this research?

You will need to complete a Consent Form which will be emailed to you.

Will I receive feedback on the results of this research?

Yes, I will let you know your results via email and if you are interested I can send you a copy of the published manuscript.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, John Cronin john.cronin@aut.ac.nz or call at 64 9 921 9999 ext 7523.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTECH, Kate O'Connor, ethics@aut.ac.nz, 64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Email Bret Contreras at bretcontreras@hotmail.com.

Project Supervisor Contact Details:

Email John Cronin at john.cronin@aut.ac.nz or call at 64 9 921 9999 ext 7523.

Approved by the Auckland University of Technology Ethics Committee on 16 Dec 2013, AUTECH Reference number 13/375

Participant Information Sheet



Date Information Sheet Produced:

30 July 2014

Project Title

Kinematic, Kinetic and Morphological Adaptations to Training with Various Hip Extension Exercises

An Invitation

Hello! My name is Bret Contreras and I am currently seeking my PhD in Sports Science from AUT University. I will be looking at the transfer of various hip strengthening exercise to sports performance and learning a great deal about the squat and hip thrust exercises. I am seeking volunteers to participate in my research project and I hope that you choose to accept my invitation. Please be aware that your participation is completely voluntary and you can withdrawal from data collection at any point in time prior to completion. If you decide not to accept my invitation, I completely understand and appreciate you taking the time to read and consider this invitation.

What is the purpose of this research?

The purposes of this research is to 1) obtain kinematic and kinetic data, which will inform my culminating training study for my PhD thesis, and 2) obtain morphological and performance data. In particular, I am interesting in measuring the following variables during the squat and hip thrust exercises: vertical force, velocity, power, rate of force development, heart rate, and joint angle movements. I am also interested in determining the reliability of a novel maximum horizontal force test. Finally, I am interested in measuring vertical jump, broad jump, triple jump, 10-m dash, 40-m sprint, maximum hip thrust isometric force, maximum squat isometric force, maximum horizontal force, gluteus maximus muscle thickness, pennation angle, and fascicle length before and after a 10-week squat, hip thrust, and combined squat and hip thrust training regimen.

How was I identified and why am I being invited to participate in this research?

You were identified because you responded to a request from my blog seeking volunteers for my research. You indicated that you were between 18-35 years of age and had at least one year of strength training experience.

What will happen in this research?

You will perform sets of squats and hip thrusts while mechanical variables of interest are recorded. You will push against a wall while standing on a force plate to determine maximum horizontal pushing force. Depending on which study you partake in, you might engage in a 10-week training regimen consisting of a periodized, full body training regimen. Before and after the training regimen, you will perform various tests to measure hypertrophic, architectural, strength, speed, and power adaptations. These tests include vertical jump, broad jump, triple jump, 10-m dash, 40-m sprint, maximum hip thrust isometric force, maximum squat isometric force, maximum horizontal force, gluteus maximus muscle thickness, pennation angle, and fascicle length. A force plate, tape measure, radar gun, and ultrasound unit will be used to record data.

What are the discomforts and risks?

Being analysed via ultrasound is awkward and unnatural. This is especially true for the gluteus maximus region, which will require for the buttocks to be exposed. Lifting weights always involves risk of injury, no matter how careful you are, however, to mitigate this we wish to only include subjects with ample weight training experience. Steps will be taken to ease your comfort and safety, throughout the study.

How will these discomforts and risks be alleviated?

During ultrasonic imaging, only one side of the buttocks will be exposed, undergarments will be worn, and a sheet will be used to cover up as much of the body as possible. I will provide you with a proper warm-up and exercise instruction to minimize the risk of injury. A Certified Strength and Conditioning Specialist (CSCS) will always be present during training to oversee and ensure proper training practices.

What are the benefits?

Determining the kinematics and kinetics during back squats and barbell hip thrusts will allow coaches, trainers, and athletes to make better programming and training decisions for the purposes of glute development, thigh development, strength, power, speed, and injury prevention. Measuring the reliability of a novel maximum horizontal force test will allow coaches to utilize the test to determine improvements in pushing force via different types of programs. Determining the transfer of training from squats, hip thrusts, and combined squats and hip thrusts will greatly benefit the strength & conditioning community as it will allow for better protocols and methods.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from your health insurance company. Please check and make sure that you have insurance prior to participating in this study.

How will my privacy be protected?

Your name will be kept confidential. All data is de-identified and the results are either presented as grouped data or referred to as "subject #1," "subject #2," etc. Your personal results can be returned to you on request. What you choose to do with the data is your decision, but I request that it not be released into the public domain until after the data has been published in a peer-reviewed journal.

What are the costs of participating in this research?

There are no financial costs associated with this research, however, 45-135 minutes of your time will be needed on up to six occasions.

What opportunity do I have to consider this invitation?

Please let me know within a week if you accept this invitation.

How do I agree to participate in this research?

You will need to complete a Consent Form which will be emailed to you.

Will I receive feedback on the results of this research?

Yes, I will let you know your results via email and if you are interested I can send you a copy of the published manuscript.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, John Cronin john.cronin@aut.ac.nz or call at 64 9 921 9999 ext 7523.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTECH, Kate O'Connor, ethics@aut.ac.nz, 64 9 921 9999 ext 6038.

Whom do I contact for further information about this research?

Researcher Contact Details:

Email Bret Contreras at bretcontreras@hotmail.com.

Project Supervisor Contact Details:

Email John Cronin at john.cronin@aut.ac.nz or call at 64 9 921 9999 ext 7523.

Approved by the Auckland University of Technology Ethics Committee on 25 Sept 2014, AUTEK Reference number
14267_04092014.

Appendix 4. Abstracts of Chapters as Published, In Press, or In Review

Appendix 4a. Chapter 2: Strength & Conditioning Journal

Contreras, B., Vigotsky, A., Schoenfeld, B., Cronin, J. A review of gluteus maximus EMG activity during resisted hip extension exercise. *Strength & Conditioning Journal*, In Review March 11, 2016.

Abstract

Hip extension exercises are essential in strength and conditioning. The primary hip extensors are the gluteus maximus, hamstrings, and adductors, and the contribution of each varies throughout the hip flexion-extension arc of motion. There is a scarcity of well-conducted resistance training studies examining gluteus maximus EMG activity, and to date, no comprehensive study exists that compares the gluteus maximus EMG activity of a variety of common resisted hip extension exercises. This article reviews the current research pertaining to gluteus maximus EMG activity during resisted hip extension exercise, and provides direction for future research.

Appendix 4b. Chapter 3.1: Strength & Conditioning Journal

Contreras, B., Cronin, J., & Schoenfeld, B. (2011). Barbell hip thrust. *Strength & Conditioning Journal*, 33(5), 58-61.

Abstract

THE TECHNIQUE OF THE BARBELL HIP THRUST IS DESCRIBED AND DEMONSTRATED THROUGH THE USE OF PHOTOGRAPHS AND VIDEO IN THIS COLUMN. AN EXERCISE PRESCRIPTION IS GIVEN.

Appendix 4c. Chapter 3.2: Strength & Conditioning Journal

Contreras, B. M., Cronin, J. B., Schoenfeld, B. J., Nates, R. J., & Sonmez, G. T. (2013). Are all hip extension exercises created equal?. *Strength & Conditioning Journal*, 35(2), 17-22.

Abstract

TARGETED HIP EXTENSION EXERCISES ARE OFTEN PERFORMED TO DEVELOP STRENGTH, POWER, AND ENDURANCE IN THE HIP EXTENSORS. ALTHOUGH THESE EXERCISES CAN POSSESS SIMILAR MOVEMENT PATTERNS, BIOMECHANICALLY THE INSTANTANEOUS TORQUE AT DIFFERENT RANGES OF HIP EXTENSION VARIES DEPENDING ON BODY POSITION RELATIVE TO SPACE. FOR THESE REASONS, IT IS PROPOSED THAT: (A) HIP EXTENSION EXERCISES MIGHT TRANSFER BETTER TO SPORT ACTIONS WHERE THE REGION OF FORCE ACCENTUATION IS MOST SPECIFIC; (B) HIP EXTENSION EXERCISES MAY LEAD TO UNIQUE STRUCTURAL ADAPTATIONS; AND (C) A VARIETY OF EXERCISES MIGHT BE NECESSARY TO MAXIMIZE HIP EXTENSION STRENGTH AND POWER THROUGHOUT THE ENTIRE RANGE OF MOTION.

Appendix 4d. Chapter 4: PeerJ

Contreras, B., Vigotsky, A., Schoenfeld, B., Cronin, J. A comparison of two gluteus maximus EMG maximum voluntary isometric contraction positions. *PeerJ*, 3, e1261.

ABSTRACT

Background. The purpose of this study was to compare the peak electromyography (EMG) of the most commonly-used position in the literature, the prone bent-leg (90°) hip extension against manual resistance applied to the distal thigh (PRONE), to a novel position, the standing glute squeeze (SQUEEZE).

Methods. Surface EMG electrodes were placed on the upper and lower gluteus maximus of thirteen recreationally active females (age = 28.9 years; height = 164 cm; body mass = 58.2 kg), before three maximum voluntary isometric contraction (MVIC) trials for each position were obtained in a randomized, counterbalanced fashion.

Results. No statistically significant ($p < 0.05$) differences were observed between PRONE (upper: 91.94%; lower: 94.52%) and SQUEEZE (upper: 92.04%; lower: 85.12%) for both the upper and lower gluteus maximus. Neither the PRONE nor SQUEEZE was more effective between all subjects.

Conclusions. In agreement with other studies, no single testing position is ideal for every participant. Therefore, it is recommended that investigators employ multiple MVIC positions, when possible, to ensure accuracy. Future research should investigate a variety of gluteus maximus MVIC positions in heterogeneous samples.

Appendix 4e. Chapter 5: Journal of Applied Biomechanics

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A. Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis Electromyography Amplitude in the Parallel, Full, and Front Squat Variations in Resistance-Trained Females. *Journal of Applied Biomechanics*, 32(1), 16-22.

ABSTRACT

Front, full, and parallel squats are some of the most popular squat variations. The purpose of this investigation was to compare mean and peak electromyography (EMG) amplitude of the upper gluteus maximus, lower gluteus maximus, biceps femoris, and vastus lateralis of front, full, and parallel squats. Thirteen healthy women (age = 28.9 ± 5.1 y; height = 164 ± 6.3 cm; body mass = 58.2 ± 6.4 kg) performed 10 repetitions of their estimated 10-repetition maximum of each respective variation. There were no statistical ($P \leq .05$) differences between full, front, and parallel squats in any of the tested muscles. Given these findings, it can be concluded that the front, full, or parallel squat can be performed for similar EMG amplitudes. However, given the results of previous research, it is recommended that individuals use a full range of motion when squatting, assuming full range can be safely achieved, to promote more favorable training adaptations. Furthermore, despite requiring lighter loads, the front squat may provide a similar training stimulus to the back squat.

Appendix 4f. Chapter 7: Journal of Applied Biomechanics

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. Comparison of Gluteus Maximus, Biceps Femoris, and Vastus Lateralis EMG Amplitude for the Barbell, Band, and American Hip Thrust Variations. *Journal of Applied Biomechanics*. In Press March 11, 2016.

ABSTRACT

Bridging exercise variations are well researched and commonly employed for both rehabilitation and sports performance. However, resisted bridge exercise variations have not yet been compared in a controlled experimental study. Therefore, the purpose of this study was to compare the differences in upper and lower gluteus maximus, biceps femoris, and vastus lateralis electromyography (EMG) amplitude for the barbell, band and American hip thrust variations. Thirteen healthy female subjects (age = 28.9 years; height = 164.3 cm; body mass = 58.2 kg) familiar with the hip thrust performed ten repetitions of their ten-repetition maximum of each variation in a counterbalanced and randomized order. The barbell hip thrust variation elicited statistically greater mean gluteus maximus EMG amplitude than the American and band hip thrusts, and statistically greater peak gluteus maximus EMG amplitude than the band hip thrust ($p \leq 0.05$), but no other statistical differences were observed. It is recommended that resisted bridging exercise be prescribed according to the individual's preferences and desired outcomes.

Appendix 4g. Chapter 7: Journal of Applied Biomechanics

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A comparison of gluteus maximus, biceps femoris, and vastus lateralis EMG activity in the back squat and barbell hip thrust exercises. *Journal of Applied Biomechanics*, 31(6), 452-458.

ABSTRACT (200 words)

The back squat and barbell hip thrust are both popular exercises used to target the lower body musculature; however, these exercises have yet to be compared. Therefore, the purpose of this study was to compare the surface electromyographic (EMG) activity of the upper and lower gluteus maximus, biceps femoris, and vastus lateralis between the back squat and barbell hip thrust. Thirteen trained women ($n = 13$; age = 28.9 years; height = 164 cm; mass = 58.2 kg) performed estimated 10-repetition maximums (RM) in the back squat and barbell hip thrust. The barbell hip thrust elicited significantly greater mean (69.5% vs 29.4%) and peak (172% vs 84.9%) upper gluteus maximus, mean (86.8% vs 45.4%) and peak (216% vs 130%) lower gluteus maximus, and mean (40.8% vs 14.9%) and peak (86.9% vs 37.5%) biceps femoris EMG activity than the back squat. There were no significant differences in mean (99.5% vs 110%) or peak (216% vs 244%) vastus lateralis EMG activity. The barbell hip thrust activates the gluteus maximus and biceps femoris to a greater degree than the back squat when using estimated 10RM loads. Longitudinal training studies are needed to determine if this enhanced activation correlates with increased strength, hypertrophy, and performance.

Appendix 4h. Chapter 8: Journal of Applied Biomechanics

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A kinetic analysis of the back squat and barbell hip thrust exercises. *Journal of Applied Biomechanics*. In review March 11, 2016.

Abstract

Both the squat and hip thrust resistance-training exercises that stimulate the hip extensors. Research comparing the two, however, is scarce. Therefore, the purpose of this study was to compare kinetic and spatiotemporal variables between the squat and hip thrust. Average force, average concentric force, average eccentric force, total impulse, total work, average power, total time, and bar displacement were measured and compared using a within-subject design on subjects' 10RM. The only difference not due to chance alone was bar displacement. Although the squat elicited greater impulse, work, eccentric force, and power, it cannot be said that these differences were not due to chance alone, nor can it be said that the greater concentric force in the hip thrust was not due to chance alone. Interestingly, the hip thrust appears to have a much greater concentric-to-eccentric force ratio, which may have implications for horizontal force production in things like sprint acceleration, but further research is required to elucidate this.

Appendix 4i. Chapter 9: Journal of Strength & Conditioning Research

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., Reyneke J., McMasters T., & Cronin, J. A. Effects of a six-week squat versus hip thrust program on performance. *Journal of Strength & Conditioning Research*. In review March 11, 2016.

Abstract

Previous acute and mechanistic research from our group has suggested that the hip thrust may be an effective exercise in increasing horizontal performance, such as horizontal jump and sprint acceleration. The squat's ergogenic ability is well known and evidenced. The purpose of this study is, therefore, to compare the effects of a six-week squat versus hip thrust program in male adolescent athletes. Vertical jump, horizontal jump, 10- and 20-meter sprint, and isometric mid-thigh pull were among the measured performance variables, in addition to squat and hip thrust three-repetition maximum (3RM). Magnitude-based effect-sizes revealed possibly beneficial effects for the hip thrust compared to the squat in 10- and 20-meter sprint times and isometric mid-thigh pulls, and possibly a trivial effect in horizontal jump length. It was also revealed that the front squat was possibly beneficial for vertical jump performance. Lastly, each exercise led to greater gains in its own 3RM. These results support the force vector theory. Further research is warranted in other populations, in addition to using different protocols and combinations of exercises.

Appendix 4j. Chapter 10: Sports Biomechanics

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., Schuster, J., & Cronin, J. A. Reliability of the maximum horizontal push test. *Sports Biomechanics*. In review March 11, 2016.

Abstract

Pushing and horizontal force production are ubiquitous in sport, and may be an important factor in sprinting performance. However, no test has been developed to test an athlete's maximum horizontal force production, or pushing strength; therefore, the purpose of this study is twofold; that is, to develop a maximum horizontal push test (MHPT) and test its test-retest reliability. Nine adolescent subjects were recruited from a sport development program to complete the test on three separate occasions. The test displayed strong reliability (ICC = 0.96; CV = 5.7%). Implications of this test are many, including that ability to objectively determine an athlete's pushing strength. Future research should examine performance correlations with this test, which may increase its applicability.

Appendix 4k. Chapter 11: Journal of Strength & Conditioning Research

Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. A. Effects of a six-week squat versus hip thrust program on gluteus maximus thickness and horizontal force production in monozygotic twins: a single-subject design. *Journal of Strength & Conditioning Research*. In review March 11, 2016.

Abstract

The back squat is a commonly utilized exercise for both athletic performance and gluteus maximus hypertrophy. The barbell hip thrust is a new, horizontally-loaded exercise that elicits superior gluteus maximus electromyographic activity compared to the barbell hip thrust, and has been proposed to lead to greater gluteus maximus hypertrophy than the squat. Furthermore, due to its horizontal nature, it may carryover well to horizontally oriented activities, such as sprint acceleration. The purpose of this study was to investigate the effects of a six-week squat versus hip thrust program on gluteus maximus size and maximum horizontal push force in one pair of monozygotic twins. It was found that both interventions increased gluteus maximus size, but only the hip thrust increased maximum horizontal pushing force. The hip thrust led to greater upper and gluteus maximus growth. This study provides insight into the possible benefits of hip thrusting in those not experienced with progressive overload, and that it is a potent stimulus for gluteus maximus growth and increasing horizontal force production.

Appendix 5. Electromyography

Introduction

Scientists first began studying electricity in muscles in electric ray fish and frog legs in the mid-1600's (Clarys, 1994; Reaz et al. 2006). In 1792, researchers realized that electricity could produce muscular contractions, and in 1849, researchers discovered that they could monitor the muscles' electrical potential differences (Reaz et al. 2006). The term "electromyography" and the measure of electrical potential differences in the muscles were finally carried out in 1890.

Using electromyographic equipment, electrical potential differences within muscles or within a single muscle fiber are measured as voltages in mV or μ V between pairs of electrodes. Electromyography (EMG) is therefore the study of electricity in muscles, usually referencing voltages and called EMG amplitudes (Reaz et al. 2006; Burden, 2007). EMG signals of up to 5mV have been detected, and firing frequencies can fall anywhere in between 0 and 1,000Hz (Burden, 2007). Usually, agonist muscle behavior is examined using EMG during dynamic and isometric movements, however antagonist electrical potential differences are also measured when studying co-activation (Fee & Miller, 2012).

The electrical signals responsible for producing the contractile behavior of the muscle fibers during muscle actions are recorded during EMG experiments. Many individual motor action potentials (MAPs) are produced in time to carry out these muscle actions. A motor unit action potential (MUAP) is the sum of the electrical signals of the individual MAPs that are close to EMG electrode pairs, and a motor unit action potential train (MUAPT) is a sequence of MUAPs measured over a period of time. A

myoelectrical or electromyographic signal is the waveform formed from multiple MUAPTs from each of the detected active motor units from the electrodes (Burden, 2007). An electromyogram is an amplified myoelectric signal that is displayed by EMG equipment (Burden, 2007), which is thought to be reflective of the sum of each of the active motor unit's electrical contributions within the vicinity of the electrodes and considered a global measure of the activity of the motor units during the investigated muscle action (Farina et al. 2004b). The strength of the electrical signal is usually reported as EMG amplitude and can be filtered and reported in several ways.

Muscles

The central nervous system (CNS) produces motor unit action potentials in order to activate muscles and create joint torque. These action potentials lead to electrical potential differences in muscles, which can be measured using EMG and reported as EMG amplitude.

Muscles consist of numerous muscle fibers, which themselves consist of strings of sarcomeres arranged in parallel and in series to one another. Overlapping actin and myosin filaments within the sarcomeres allow the sarcomeres to change length. Muscle force is created when pulsed electrical signals from the CNS, deemed action potentials, are sent along efferent nerves, deemed alpha motor neurons, which ultimately reach the neuromuscular junction and propagate the muscle fibers that are part of the motor unit, deemed motor action potentials (MAP). However, the MAP must exceed the depolarization threshold in order for a MAP to be produced (Burden, 2007; Kuriki et al. 2012).

The MAP produces actin-myosin crossbridge formation, which works in concert with titin to produce muscle force (Herzog et al. 2015). Action potentials travel in one direction along the efferent nerve, however, the MAP travels in both directions from the motor point along the muscle fiber, which produces electrical potential differences in the muscle (Staudenmann et al. 2009). The MAP propagation releases calcium ions, which enable the sarcomeres to produce force; relaxation of the fibers takes place upon subsequent calcium ion reuptake.

Motor Units

A motor unit consists of an alpha motor unit and its associated muscle fibers. Motor units were previously thought to consist of the same fiber types (Staudenmann et al. 2009), however this has recently been called into question (Enoka & Duchateau, 2015). Nevertheless, the muscle fibers from each motor unit intermingle with those of other units in a random fashion, except that fibers associated with smaller motor units tend to be located deep within the muscle and fibers associated with larger motor units tend to be located superficially (Staudenmann et al. 2009).

Motor Unit Recruitment

Motor units are activated in a well-regulated order of size as neural drive is ramped up from the CNS. Smaller motor units are recruited initially, with larger motor units being subsequently recruited (Staudenmann et al. 2009). Larger motor units can produce 100 times more force than smaller motor units. This orderly recruitment is known as Henneman's size principle, which is named after the researcher who originally discovered it (Henneman et al. 1965), and it has withstood scrutiny for the past 50 years.

Motor Unit Firing Frequency

Frequent production of action potentials is needed to sustain or increase force production during contractions, since muscle fibers immediately relax after they produce force. For this reason, the CNS commonly produces numerous action potentials in sequence in a short time frame. The rate of action potential production is deemed motor unit firing frequency or rate coding. A state of tetanus is reached in the muscle fibers associated with the motor unit once firing frequency exceeds approximately 30-40 pulses per second, meaning that there is no relaxation period between MAPs. Therefore, motor unit firing frequencies above 40 pulses per second fail to increase force production in the muscle fibers (Staudenmann et al. 2009).

Determinants of EMG Amplitude

No matter which way EMG amplitude is filtered, processed, and reported, the size of its recording consists of direct physiological processes which generate and transmit myoelectricity, combined with a indirect associated factors which affect the characteristics of the recording as well (Kamen & Caldwell, 1996). Recordings are highly affected by factors such as noise from the equipment, from the surrounding environment, and from the nature of the signal itself.

Effects of Noise on EMG Amplitude

Noise may disrupt the electromyogram, which is why researchers attempt to utilize methods that maximize the signal-to-noise ratio (Chowdhury et al. 2013). Noise can arise from several factors. First, from the electrical equipment itself, especially if it is low in quality. Second, from background electromagnetic radiation. Third, from motion artifacts, since electrode position is altered by movement. And fourth, from the randomness of motor unit firing patterns (Reaz et al. 2006; Chowdhury et al. 2013).

Other Factors Affecting EMG Amplitude

After accounting for equipment and environmental noise, which interfere with the electromyogram, there are still numerous factors that impact on the size of the electrical potential differences that are recorded from muscle. De Luca's 1997 review of EMG sparked researchers to begin grouping factors affecting EMG into causative, intermediate, and deterministic headings, with causative consisting of extrinsic and intrinsic factors (De Luca, 1997; Reaz et al. 2006; Burden, 2007).

Causative and Intermediate Factors - Extrinsic

Factors that alter the signal on account of the type of equipment and how it is utilized are known as extrinsic causative factors. One such extrinsic factor is the EMG electrode. The configuration of the electrode, including the area covered, the shape, and the distance between electrodes, the location of the electrodes in relation to the innervation point, the myotendinous junction, and other muscles, and the direction of the electrode in relation to the general direction of the muscle fibers, can all impact the recorded signal (De Luca, 1997). Because MAPs are propagated in two directions along the muscle fiber once the depolarization threshold at the synapse has been exceeded, the placement of the electrodes is important, since the observed voltage could essentially cancel itself out if the electrode pair is placed on either side of the point at which the muscle fiber is innervated, which is known as the motor point (Burden, 2007).

It has been recommended therefore that electrodes be placed between the motor point and the tendon. Multiple collections of guidelines are available for identifying these points, for example Zipp, 1982. Securing electrodes properly is increasingly important

when testing in warm environments or when excessive sweating is present, as this can interfere with the sticky surface's ability to adhere to the skin.

Causative and Intermediate Factors - Intrinsic

Factors that are affected by physiology, including motor unit recruitment, blood flow within the muscle, the diameter of the muscle fiber, the active fiber depth within the muscle, the thickness of non-muscle tissue in between the active muscle fibers and the electrode (De Luca, 1997), and the length of the muscle (Kamen & Caldwell, 1996), are known as intrinsic causative factors.

Factors that are affected by extrinsic or intrinsic factors which impact on the resulting EMG signal, including differences in electric potential in neighboring muscles that produce crosstalk, or the conduction velocity of motor neuron action potentials (De Luca, 1997), are known as intermediate factors.

Deterministic Factors

Factors responsible for driving the action potential from the CNS, which therefore impact the size and shape of the electromyogram are known as deterministic factors.

Deterministic factors include active motor unit number, motor unit firing frequency, the mechanical interactions occurring between muscle fibers, and the stability of recruitment of motor units (De Luca, 1997).

It was traditionally thought that three main factors arisen from the CNS impacted EMG amplitude: the extent of the motor unit recruitment, motor unit firing frequency, and synchronization of electrical impulses (Behm, 1995). Recent work, however, has casted

serious doubt on synchronization as an important factor (De Luca and Erim, 1994, Duchateau et al. 2006, De Luca and Contessa, 2012, Farina and Negro, 2015).

Measuring EMG Amplitude

Measuring electric potential difference within muscles using EMG can involve different types of electrodes, different normalization methods, and a variety of data processing methods. For this reason, comparing EMG studies can be difficult and problematic. A keen understanding of these key features of EMG research is therefore important.

Electrode Type

Two primary options exist for the hardware when measuring electric potential difference within muscles using EMG. Hardware can either be non-invasive and involve the use of surface electrodes, or invasive and involve the use of fine-wire electrodes. Both types of EMG utilize pairs of electrodes which are placed upon or inside a muscle to measure the voltage between the pairs (Reaz et al. 2006). There are pros and cons to both types of EMG electrode types, however, neither detects individual MAPs or MUAPs. Moreover, in order to detect signals from individual motor unit action potential trains (MUAPTs), fine wire electrodes or special arrays of tiny surface electrodes are required. Finally, it is generally understood that surface electrodes only detect final resulting electromyographic signals (Burden, 2007).

Surface Electrodes

Surface electrodes are placed upon the surface of the skin above the muscle being measured. One pair of electrodes is most commonly used, however, recently researchers have begun using multiple pairs of electrodes along the entire length of muscles in order to receive a more comprehensive picture and improve reliability and validity (Farina et

al. 2014). Only the voltage in the muscle fibers that are close to the surface of the skin is detected by surface electrodes, which can be problematic since during a muscle action, muscle fibers are quasi-randomly innervated at any given moment (Reaz et al. 2006). This contributes to the seemingly random oscillating signal that alternates between positive and negative voltages throughout the time course of the muscle action.

Crosstalk

Between adjacent electrode placement sites on the same muscle, or on adjacent antagonist or co-contracting muscles, crosstalk can occur. Crosstalk was originally thought to be a serious limitation for surface EMG, but research has shown this fear to be less problematic than once assumed (Burden, 2007). Careful electrode placement plays a large role in preventing or reducing the problem of crosstalk. If electrode pairs are spaced further than 2-3 cm apart, the extent of crosstalk is largely diminished. This was demonstrated by Winter et al. (1994), where it was shown that crosstalk on the quadriceps was 49% at inter-electrode distances of 1cm, 13% at 2 cm, and 4 % at 3cm. On the biceps, inter-electrode pair distances from 2 – 6 cm exhibited similar low levels of crosstalk, indicating that 2 cm distances is fine for this muscle (Beck et al. 2005).

Fine Wire Electrodes

Fine wire EMG research involves placing electrodes directly into the muscle. This invasive approach was originally thought to interfere with muscle function, however, fine wire electrodes inserted into the index finger muscles failed to negatively impact force output (Burgar et al. 1997). Moreover, fine wire electrodes have a 93% success rate for correct placement into 60 different muscles. It may be possible within a single muscle fiber the electric potential difference, which is not the case with the usage of surface electrodes (Reaz et la. 2006).

Relationship Between Surface and Fine Wire Electrodes

Surface EMG amplitude has been positively correlated with fine wire EMG amplitude in numerous studies (Bouisset & Maton, 1972). It is especially the case with larger muscles such as the gluteus medius (Semciw et al. 2014), the lower limb muscles (Chapman et al. 2010), and the quadriceps and hamstrings (Jacobson et al. 1995). However, surface EMG amplitude in certain smaller and deeper muscles such as those in the rotator cuff are less well correlated with fine wire EMG amplitude (Waite et al. 2010; Allen et al. 2013; Rajaratnam et al. 2014). Whether this happens to be a function of the smaller size or the deeper location is unclear, especially when considering that some abdominal muscles, the quadratus lumborum, and the psoas display good correlations (McGill et al. 1996).

Normalization

Normalization methods are used to better enable comparisons of EMG amplitude. To normalize EMG data, it is necessary to divide the magnitude of the EMG amplitude recorded during the conditioning being tested by the EMG amplitude recorded during a reference contraction. Dividing by the same terms eliminates the reference to voltage, thereby producing a unitless percentage of the value for the reference contraction, for example 90% of MVIC. It is not mandatory to normalize EMG data, however, it is when comparisons are made between trials that require the reapplication of electrodes, are performed comparing between different muscles, or comparing between different groups (Burden, 2010).

Importance of Normalization

Normalization is essential when comparing several muscles or subdivisions within the same muscle, as numerous causative factors may differ between the measured areas. Lehman and McGill (1999) clearly demonstrated this when they compared the EMG amplitude between the upper and lower rectus abdominis during the trunk curl exercise. When comparing the absolute EMG amplitudes in mV, the upper region was much higher than the lower region. However, when normalized, the EMG amplitude showed no differences between the upper and lower regions.

Reference Contractions

The process of normalizing requires a reference contraction to normalize to. Usually the reference contraction is an MVIC, as performed in a generally agreed upon position for each muscle. However, other possibilities for MVIC's exist (Burden, 2010). Despite the fact that MVICs are the most common reference contractions used in the literature, they are not without criticism. EMG amplitude often exceeds the MVIC position during dynamic, high force muscle actions, indicating that MVICs do not in fact represent the maximum activation capacity of muscles (Burden, 2010). Moreover, MVIC reference contractions sometimes display lower reliabilities when compared to submaximal isometric muscle actions (Yang and Winter, 1983; Burden, 2007). Therefore, some researchers believe that normalization should utilize submaximal isometric contractions at below 80% of MVIC (De Luca, 1997; Burden, 2007). Later research has yielded different results, however, with MVICs showing similar or greater reliabilities than submaximal isometric contractions (Lehman, 2002; Burden et al. 2003; Rouffet and Hautier, 2008). There is currently no strong consensus pertaining to ideal types of reference contractions (Burden, 2010).

Reference Contraction Options

Burden (2010) has identified 8 different normalization methods. These methods utilize variations of MVIC, maximum voluntary dynamic contraction (MVDC), submaximal voluntary isometric contraction (SVIC), and submaximal voluntary dynamic contraction (SVDC) approaches. These can differ by joint angle and joint range of motion (ROM). The 8 unique normalization methods include:

- Average EMG in the task investigated (average TASK)
- Peak EMG in the task investigated (peak TASK)
- Peak EMG in a SVIC
- Peak EMG in a SVDC
- Peak EMG in an MVIC with arbitrary joint angle (arbitrary angle MVIC)
- Peak EMG in an MVIC at a specific joint angle to the task (specific angle MVIC)
- Peak EMG in a MVDC through a specific joint ROM to the task (specific MVDC)
- Peak EMG during an isokinetic MVDC at a specific speed and through a specific joint ROM to the task (isokinetic MVDC)

Comparing Normalization Methods

Inter-Individual Variability

A major problem in sports science that makes it difficult to identify group effects, such as when comparing EMG amplitude in a particular muscle between two exercises in order to figure out which elicits greater muscle activation, is inter-individual variability. Certain normalization methods have been found to reduce inter-individual variability, which is quite valuable depending on the circumstance. Peak and average TASK have been shown to reduce inter-individual variability in EMG amplitude when compared to

other normalization methods (Burden 2010), which makes them advantageous when investigating group effects. On the other hand, the same normalization methods can obscure differences between two groups of subjects, for example powerlifters versus sprinters, so the normalization method must be carefully considered. It is not clear whether normalizing to the task being examined will eliminate some of the features of the condition being measured (Burden, 2010).

Usage in Practice

There is currently a lack of clarity pertaining to how peak and average TASK affects the touches of an EMG study. Therefore, MVIC is commonly recommended for slow speed muscle actions (Burden, 2010; Ball & Scurr, 2013). However, MVIC may not be the most appropriate normalization method for high speed muscle actions (Ball & Scurr, 2013), especially since it's not uncommon during high speed sports movements to find percentages of EMG that exceed 100% of MVIC (Kyrolainen et al. 2005; Liebenberg et al. 2011).

Data Collection, Reduction, and Processing

The voltage across electrodes constantly changes due to the stream of action potentials sent down the motor neurons when recording EMG amplitude. This constantly changing voltage produces a waveform when plotted as a graph over time, which is referred to as an electromyogram (Kuriki et al. 2012). Different calculations are used to assess the overall strength of the waveform, and the appropriate method must be carefully selected according to the goals of the investigation. Before the signal is recorded, however, strong efforts should be made to maximize the signal to noise ratio.

Data Collection

Electrode Attachment

Optimal equipment configuration and electrode placement according to standard guidelines is mandatory for maximizing the signal to noise ratio during data collection (Burden, 2007). Moreover, preparations to the skin must be carried out before applying electrodes. The skin is typically cleaned with soap and water, then it is dry shaved using a disposable razor. Sometimes a pad soaked in rubbing alcohol is used as well (Clancy et al. 2002; Burden, 2007). The impedance associated with the skin-electrode connection is reduced and the quality of the signal being recorded is enhanced when using these practices (Clancy et al. 2002).

Sampling, Signal Amplification, and Filtering

Recorded data from electrodes is usually sampled by EMG equipment at 1,000-2,000 Hz (Burden, 2007). In other words, single data points are recorded 1,000 – 2,000 times per second. Next, these data points are amplified, and then plotted as an amplitude over time on the electromyogram. When amplifying the data, careful calibration must be undertaken since excessive gain can cause some of the largest EMG amplitudes to exceed the maximum output voltage which causes them to be clipped, whereas insufficient gain can cause some of the smallest EMG amplitudes to be lost and unobserved (Burden, 2007). Elements of noise that have infiltrated the signal can be eliminated by filtering the signal (De Luca et al. 2010). Noise can arise from extrinsic sources including power line, cable motion, and skin to electrode movement artifacts, as well as intrinsic sources including thermal and electrochemical (De Luca et al. 2010). To optimally filter the data, it is necessary to remove the noise elements that differ in frequency from the signal, which requires upper and lower frequency limits to be set (De Luca et al. 2010). The point where noise amplitude appears to exceed the signal

amplitude is at 400-450 Hz, therefore low pass filters are generally set at this level.

High pass filters, however, are generally set at 5-20 Hz (De Luca et al. 2010). In order to remove contamination from electrocardiographic interference, especially when examining EMG amplitude in torso muscles, high pass filtering is typically performed (Redfern et al. 1993).

EMG Amplitude Processing Options

A large array of data must be converted to a single value when assessing EMG amplitude in order for it to be compared with other values, which is known as EMG amplitude processing (Merletti @ DiTorino, 1999). There are multiple processing options, each of which are recorded relative to a certain time window, which can be the entire duration of the muscle action or a particular window of time during the muscle action, for example 500 ms. When converting the waveform, the most common data reduction and processing options are:

- Integrated EMG amplitude (I-EMG)
- Average rectified EMG amplitude (A-EMG)
- Root mean square (RMS) of the rectified waveform (RMS-EMG)
- Linear envelope (LINEAR-EMG)
- Peak EMG amplitude (P-EMG)

Details of Different Options

Integrated EMG (I-EMG)

The electromyogram must be rectified before calculating the area under the curve (AUC) when calculating I-EMG. Since every electromyogram has both positive and negative voltages, rectification either removes or reverses the negative values. Half-wave rectification involves removing the negative values, whereas reversing the

negative values is known as full-wave rectification. The resulting waveform is entirely positive and is then integrated to find the AUC (Burden, 2007).

Average Rectified EMG (A-EMG)

A-EMG, also called the average rectified value, average integrated EMG, mean absolute value, and mean amplitude value (Burden, 2007), is similar to I-EMG, except that it's divided by the time period in question, which yields the average value (Burden, 2007).

Root Mean Square EMG (RMS-EMG)

Summing all of the squared values of each instantaneous EMG amplitude (in mV or μ V) over a set time period, then dividing by the number of seconds in the time period, and then finally taking the square root of this number calculates RMS-EMG (Burden, 2007). Since squared values are examined, rectification is not necessary since the square function automatically removes the negative values.

Peak EMG (P-EMG)

The highest recorded EMG amplitude value in any given time period is known as P-EMG, and it can be measured according to the raw signal, or following one of the other data processing options (A-EMG, I-EMG, RMS-EMG, etc.) across the measured time windows during the muscle action being investigated. It is considered a good indicator of how large the magnitude of the EMG amplitude can be as a result of a particular muscle action, however, the extent to which this could be impacted by noise and causative factors is currently unclear. Given that the single largest value is recorded during a given time period, the reliability of P-EMG would naturally be expected to be lower than methods that utilize averages.

Linear Envelope EMG (Linear-EMG)

LINEAR-EMG requires the application of a low-pass filter to the rectified waveform. The precise parameters of the low-pass filter varies between studies, making Linear-EMG a more difficult option to compare (Burden, 2007).

Differences Between Options

Validity

I-EMG and A-EMG have each been received their share of criticism. Experts have stated that the integral of a waveform has no inherent validity in the context of muscle activation, and therefore I-EMG and A-EMG do not mean anything (see reviews by De Luca, 1997; Burden, 2007; Staudenmann et al. 2009). These researchers find RMS-EMG to be the preferred measurement, since the RMS of an electrical waveform is representative of the voltage that would be achieved if the electric current were constant. Nevertheless, I-EMG has indeed been shown to be correlated with external mechanical work done (Bouisset & Goubel, 1971; 1973)

Reliability

Some data processing measures of EMG amplitude appear to be more reliable and display less inter-individual variability or intra-individual variability than others (see reviews by Burden, 2007; Staudenmann et al. 2009). These researchers believe A-EMG to be the preferred measurement, as it appears to be more stable and more linearly related to muscle force over a more broad range of force levels (Staudenmann et al. 2009).

Interpretation

Researchers believe that P-EMG provides a good indicator of the maximal EMG amplitude elicited during performance of the muscle action, whereas A-EMG provides a better indication of the overall EMG amplitude when averaged across the entire movement (Hibbs et al. 2011). Certain dynamic exercises display very different peak and average EMG amplitudes, especially when a muscle is highly involved at one end of the range of motion (ROM) and not so involved at the other end of the ROM. For example, during the squat exercise, hip extension torque requirements are low at the top of the movement but large at the bottom of the movement, so this might lead to high P-EMG but low A-EMG outputs.

Drawing Inferences from EMG

Researchers first conduct experiments whereby electric potential difference within muscles are measured using EMG, then they are expected to draw inferences about what this might mean for other variables. These inferences are made when taking a logical leap from information that has been directly measured to make predictions about something that has not been directly measured.

Researchers commonly suggest that EMG measurements can be used as a proxy for measures of voluntary activation, muscle fiber recruitment, strength building potential, and muscle hypertrophy potential. Carlo De Luca, a renowned researcher, has suggested that incorrect inferences drawn from EMG measurements might be due to the fact that EMG is “too easy to use and consequently too easy to abuse” (De Luca, 1997).

Voluntary Activation

When it is claimed that EMG measurements provide an indicator of the changes or differences in voluntary activation, it is usually erroneous due to confusion regarding the terminology being used. Voluntary activation is the percentage of involuntary force production that can be exerted during a MVIC, which is most commonly carried out using the interpolated twitch technique (Shield and Zhou, 2004). The interpolated twitch technique administers an external electrical stimulus to a muscle during the MVIC, which recruits motor units that have not been recruited, causing the muscles to contract more strongly and generate more force (Herbert and Gandevia, 1999; Shield and Zhou, 2004; Gabriel et al. 2006). Voluntary activation can then be calculated as the MVIC force divided by the involuntary force and expressed as a percentage. Voluntary activation therefore provides a mathematical indicator of the extent to which the natural force-producing capability possessed by a muscle can be voluntarily assessed. If voluntary activation is measured before and after a resistance-training program, it can provide insight as to whether or not neural drive increased.

Most commonly, EMG is discussed in strength training circles within the context of voluntary activation following a resistance training intervention (Arabadzhev et al. 2014). Under these circumstances, researchers typically report that EMG amplitude increased as well as strength (either 1RM or MVIC force), and this leads them to thereby infer that neural drive or voluntary activation has enhanced (Arabadzhev et al. 2014). The problem with drawing this inference is that peripheral factors also impact EMG amplitude. Peripheral factors include muscle fiber type composition, blood flow, muscle fiber diameter, the location of the electrode on the muscle fiber, the quantity of subcutaneous tissue (De Luca, 1997; Reaz et al. 2006) and the changes in the intracellular action potential (IAP) duration. IAP duration most likely follows from

changes in calcium ion levels (Arabadzhev et al. 2014). In addition, the relationship between voltage, current, and resistance (Ohm's law or $V = IR$, where v = voltage, I = current, and R = resistance) predicts that increases in muscle size (and therefore resistance) leads to proportional increases in the voltage required (and therefore EMG amplitude measured) for the same current. Since these peripheral factors also change over time including when performing resistance training leading to muscular hypertrophy, researchers have more recently stated that it is not appropriate to conclude that changes in EMG amplitude imply that neural factors are solely responsible for the observed increases in muscular strength following a resistance training program (Arabadzhev et al. 2014).

Muscle Fiber Recruitment

Some researchers have recently implied that EMG amplitude can be used as a proxy for muscle fiber recruitment (e.g. Jenkins et al. 2015; Looney et al. 2015). This claim has been criticized (Vigotsky et al. 2015a; Vigotsky et al. 2015b) on the basis that the electric potential difference within muscles is a function of both muscle fiber recruitment and motor unit firing frequency, in addition to several additional peripheral factors (Kuriki et al. 2012). Therefore, when EMG amplitude increases are observed, it could arise from increases in muscle fiber recruitment, increase in motor unit firing frequency, or alterations in one of the peripheral factors. As a result, motor unit recruitment, in addition to certain aspects of the size principle, cannot be detected by examining EMG amplitude (Ertas et al. 1995).

Relative Load

Researchers have recently used EMG to explore differences in voltage within muscles during exercise performed with light and heavy loads (e.g. Jenkins et al. 2015; Looney

et al. 2015). Where EMG amplitude is greater in the higher relative load condition, it has been suggested that this implies that muscle fiber recruitment is also higher. However, this ignores the possibility that motor unit firing frequency or changes in peripheral factors produced the differences between the two conditions. Although Henneman's size principle still describes the order in which motor units are recruited (Henneman et al. 1965), muscle fiber recruitment and EMG amplitude do not display a linear relationship. When MVIC is produced, there is always full recruitment, in addition to increases in motor unit firing frequency. Some muscles plateau in muscle fiber recruitment at around 50% of maximum voluntary isometric contraction (MVIC) levels. These muscles rely upon increases in motor unit firing rate for additional increases in force up to 100% of MVIC). Large muscles reach full recruitment at around 80 – 90% of MVIC (Masakado, 1994). Currently it is unclear as to whether this is related to the number of muscle fibers innervated by each motor unit, although it is thought that muscles that control fine movements have fewer fibers per motor unit, whereas large muscles that control larger movements have many more fibers per motor unit (Kuriki et al. 2012).

Muscular Failure

Researchers have recently used EMG to explore differences in voltage within muscles during fatiguing exercise. Early work in this area led researchers to believe that the increases in EMG amplitude observed was due to increasing motor unit recruitment, with additional muscle fibers being called upon to support fatigued fibers (Edwards & Lippold, 1956; Arabadzhiev et al. 2010). However, it has been shown that much of the increase in EMG amplitude measured under fatiguing conditions is due to changes in peripheral factors, including increased intracellular action potential (IAP) duration

(Dimitrova et al. 2003; Arabadzhiev et al. 2010), which is believed to be the result of increased calcium ion availability (Arabadzhiev et al. 2014).

Muscle Hypertrophy

Despite that EMG amplitude cannot be taken as a proxy measure of muscle fiber recruitment (Vigotsky et al. 2015a), there are some indications that EMG amplitude is related to the long-term changes in muscle size under certain conditions. EMG amplitude is correlated with fMRI and has been shown to be an accurate measure of activation (Adams et al., 1992; Dickx et al., 2010). Recent research has shown that fMRI activation is a good predictor of hypertrophy and muscle protein synthesis (Wakahara et al. 2012; Wakahara et al. 2013). This may be due to the relatively close relationship between EMG amplitude and muscle force production, which displays a linear relationship under certain conditions, as explained below. However, emerging research has failed to show a link between regional EMG amplitude and regional muscle hypertrophy (Earp et al., 2016). The researchers cited technological constraints and intramuscular differences in muscle structure as possible explanations for this occurrence.

Muscle Force Production

Most inferences drawn from electric potential difference within muscles are not valid, however, inferences pertaining to tension within a muscle by proxy by recording EMG amplitude can be undertaken with more confidence. De Luca (1997) referred to muscle force production, assuming carried out under non-fatiguing conditions, as an example of where EMG amplitude can be used to draw inferences about muscle force. However, in order to draw this inference, De Luca (1997) carefully specified that it was necessary

to ensure correct electrode placement between the innervation point and the musculotendinous junction and to avoid detecting cross-talk from neighboring muscles.

Isometric and Dynamic Force and EMG

The relationship between EMG amplitude and isometric or slow-speed dynamic force production is relatively strong. When the force is altered, this relationship diminishes on account of the behavior of the tendons and connective tissue (Disselhorst-Klug et al. 2009). To reiterate, under isometric or slow-speed dynamic conditions, EMG amplitude provides good insight into the maximum force-producing abilities of a muscle.

However, the relationship between the EMG and dynamic force production is less strong than the equivalent relationship with isometric force production. The shortening and lengthening phases possess different relationships, as EMG amplitude is lower for the same force output exhibited during lengthening muscle actions compared to similar shortening muscle actions (Disselhorst-Klug et al. 2009). Peripheral factors can affect the relationship, particularly those such as muscle length, which can change acutely. When muscles lengthen or shorten, this alters the cross-sectional area of the muscle fiber, which appears to change the muscle conduction velocity (Kamen & Caldwell, 1996) and the geometry of the region of the muscle being measured.

Linear or Non-Linear

Currently, the linearity of the relationship between EMG amplitude and force production during both isometric and slow, controlled dynamic muscle actions is unclear. With certain parameters, some researchers have found a fairly linear relationship, including when force is sub-maximal, whereas other researchers have found a non-linear relationship (e.g. Lawrence & De Luca, 1983; Herzog et al. 1998; Onishi et al. 2000). EMG amplitude during isometric contractions has been theorized to

increase with the square root of the generated force, so long as the motor units are activated independently (see Lawrence & De Luca, 1983). The nature of the relationship may depend upon the inter-relation between motor unit recruitment and motor unit firing frequency (Solomonow et al. 1989), with linearity being present when full motor recruitment occurs prior to motor unit firing frequency occurring, and non-linearity occurring when motor unit recruitment and motor unit firing frequency increase together to produce greater EMG amplitude and muscle force. Different muscles may therefore display different EMG-force relationships due to their unique motor unit recruitment strategies (Lawrence & De Luca, 1983).

Muscle Force in Fatiguing Muscle Actions and EMG

Under fatiguing muscle actions, such as when multiple repetitions of a dynamic exercise are carried out to muscular failure or during sustained isometric muscle actions, the linearity between EMG amplitude and muscle force begins to reduce and cannot be relied upon with certainty (Milner-Brown & Stein, 1975; Perry & Bekey, 1981; Lawrence & De Luca, 1983; Korner et al. 1984; Hof, 1997; Onishi et al. 2000). Drawing inferences about the muscle force produced during fatiguing muscle actions is therefore not appropriate, because EMG amplitude increases throughout the set but the tension within the muscle does not necessarily increase proportionally.

Exercises, Isometric Positions, Muscle Force, and EMG

Non-fatiguing exercises and isometric positions can both be compared with one another with respect of their ability to produce tension within muscles using EMG amplitude measurements. For example, two different exercises or isometric positions may be performed with maximal effort, but one exercise will elicit greater activation of a muscle compared to the other. This could happen on account of different patterns of

synergist muscle involvement in each of the two exercises, or it be due to one exercise possessing a more favorable muscle length based on its position on the active length-tension curve. Either way, it is likely that superior muscular adaptations will be realized with the exercise that elicits greater activation of the muscle.

Reliability

It is important when taking measurements to be confident about their reliability. When measurements are reliable, they routinely produce the same result (output) for the same performance (input). Reliability can be measured in three ways: inter-rater reliability, intra-rater reliability, and test-re-test reliability. Each contribute to the overall assessment of reliability of a measurement, however, when measuring EMG, the most important factor is test-re-test reliability, since EMG measurements are affected almost entirely by the equipment and the subject and not by the rater taking the measurements.

Test-Re-test Reliability

Test-re-test reliability is assessed when measurements of the outcome are taken on at least two occasions. For example, during two separate performances of the back squat exercise, EMG amplitude could be recorded and compared. When measuring EMG amplitude, test-re-test reliability incorporates the inherent variability in the individual performance, in the behavior of the rater, or in the use of the equipment.

Test-re-test reliability can be measured via the intra-class correlation coefficient (ICC), the standard error of measurement (SEM), the minimum difference to be considered real (MD), and the coefficient of variation (COV). The SEM and MD are the most important measures of test-re-test reliability in practice, since they allow strength coaches or physiotherapists to make comparisons in performance between individuals

(SEM) or performances by the same individual on two separate occasions (MD). The ICC and the COV, however, are more relevant when assessing the reliability of a research tool, including EMG.

Intra-Class Correlation Coefficient (ICC)

ICC's measures the magnitude of variance that arises from different individuals vs. the variance that arises from measuring multiple occasions. When a high ICC is calculated, it means that most of the variance in a data set is caused by individual differences.

When a low ICC is calculated, it means that most of the variance takes place between multiple tests. The magnitude of an ICC is dependent on the level of accuracy of the outcome that is desired in addition to the between-individual variability in the tested population. In practice, the typical ICC standards are:

- Trivial ($r < 0.1$)
- Small ($r = 0.1 - 0.3$)
- Moderate ($r = 0.3 - 0.5$)
- Large ($r = 0.5 - 0.7$)
- Very large ($r = 0.7 - 0.9$)
- Nearly perfect ($r > 0.9$)

Coefficient of Variation (COV)

COV's can either be calculated between individuals or within individuals. Between individual calculations are expressed as a percentage and are relative measures of standard deviations (SD) of all performances in a group of individuals divided by the mean (M) of the same performances, $(SD/M \times 100)$. The COV represents how broadly spread the performances of all individuals are in relation to the mean performance. By measuring the relative measure of the standard deviation of single individuals across

multiple performances and then expressed as percentage of the mean, within individual COV's can be calculated (Hopkins, 2005). This measurement produces an assessment of the variability within each individual and provides an indication as to how likely a particular individual is to produce a similar optimal performance on every occasion.

Test-Re-Test Reliability of EMG Amplitude

Comparing Isometric and Dynamic Muscle Actions

Isometric muscle actions, whether maximal or submaximal, produce greater reliability in EMG amplitude than their dynamic counterparts. When comparing the test-re-test reliability of the quadriceps and hamstrings during MVICs, jumping tasks, and cutting tasks, Fauth et al. (2010) found that the reliability was greater during the isometric muscle actions ($ICC = 0.94 - 0.97$) than the jumping ($ICC = 0.83 - 0.97$) and cutting ($ICC = 0.78 - 0.96$) muscle actions. Some recent studies, however, have concluded that the two types of external resistance provide similar levels of test-re-test reliability. For example, Jenkins et al. (2015) found that the EMG reliability was similarly high during a 1RM knee extension test for the rectus femoris, vastus lateralis, and vastus medialis muscles ($ICC = 0.88, 0.83$ and 0.94) and an isometric MVIC knee extension ($ICC = 0.81, 0.86$ and 0.78).

Comparing Postures

MVICs and SVICs can each be performed in seated, standing, prone, or supine positions. Jackson et al. (2008) performed a comprehensive study that compared the COV of the EMG amplitude (linear envelope) in both the thoracic and lumbar erector spinae during MVICs and SVICs in prone, seated, and standing trunk flexion tasks. They concluded that the COV was reduced and therefore more reliable during prone

tasks than during seated or standing tasks, which suggests that posture has an effect on the reliability of the EMG amplitude.

Comparing MVICs and SVICs

Numerous studies have compared the reliability between EMG amplitude during MVICs and SVICs, and many have found SVICs to be more reliable than MVICs (Kollmitzer et al. 1999; Dankaerts et al. 2004; Ha et al. 2013). When assessing the intra-session and inter-session test-re-test reliability of the normalized EMG amplitude in MVICs and SVICs during trunk movements in individuals with and without low back pain, Dankaerts et al. (2004) found that MVIC and SVIC test-re-test reliability both displayed good intra-session ($ICC = 0.91$). However, only SVIC test-re-test reliability was good inter-session, while MVIC test-re-test reliability was moderate ($ICC = 0.88$ vs. 0.70). When comparing the ICC and COV of the EMG amplitude for both surface and fine wire electrodes in cervical extension between MVICs and SVICs using an isokinetic dynamometer, Burnett et al. (2007) found that reliability was high for both MVICs ($ICC = 0.91 - 0.99$; $COV = 9.2 - 20.0\%$) and SVICS ($ICC = 0.95 - 0.98$, $COV = 13.5 - 13.7\%$) but no difference existed between conditions. During prone, seated, and standing trunk flexion tasks, Jackson et al. (2008) compared the COV of the EMG amplitude (linear envelope) in the thoracic and lumbar erector spinae between MVICs and SVICs. No differences in COV between the MVIC and SVIC conditions existed for prone tasks, but for standing and seated tasks, the reliability between MVIC and SVIC differed between muscles and exhibited no clear pattern. When comparing the ICC of the EMG amplitude (RMS) in the infraspinatus between two MVICs and SVICs during external shoulder rotation tasks, Ha et al. (2013) found that the ICC was much higher for the SVIC ($ICC = 0.98$) than for the MVICs ($ICC = 0.42 - 0.73$).

Comparing Intra-and Inter-Session Reliability

The majority of EMG reliability studies investigate either test-re-test reliability in a single testing session or on different testing sessions, but not both. The studies that have compared both intra-session and inter-session test-re-test reliability have found inter-session to display markedly lower reliability than intra-session (Kollmitzer et al. 1999; Dankaerts et al. 2004; Oskouei et al. 2013). When assessing both intra-session and inter-session test-re-test EMG reliability in the forearm muscles, Oskouei et al. (2013) reported that intra-session reliability was high ($ICC = 0.90$) but inter-session reliability was poor ($ICC = <0.50$). Dankaerts et al. (2004) assessed the intra-session and inter-session test-re-test EMG reliability in both MVICs and SVICs during trunk movements in individuals with and without low back pain (LBP) and found that SVIC reliability was good both inter- and intra-session ($ICC = 0.88 - 0.91$), however, MVIC reliability was only good intra-session ($ICC = 0.91$) and moderate inter-session ($ICC = 0.70$).

Comparing Surface and Fine Wire Electrodes

Although a large number of reliability studies involve surface EMG, it is quite rare to find reliability studies that have employed both surface and fine wire electrodes. Burnett et al. (2007) compared the EMG ICC and COV in both surface and fine wire electrodes during cervical extension between MVICs and SVICs using an isokinetic dynamometer. Surface electrodes tended to display slightly better reliability than fine wire electrodes across MVICs and SVICs ($ICC = 0.98 - 0.99$; $COV = 9.2 - 13.7\%$ vs. $ICC = 0.91 - 0.95$; $COV = 13.5 - 20.0\%$).

Effect of Familiarization

A lack of familiarity has been proposed as a factor that may impede the test-re-test reliability of MVICs (Ball & Scurr, 2013). This may explain why many studies have

found superior EMG test-re-test reliability when using SVICS. However, familiarization has not always produced the expected improvement over time when investigated in studies. When exploring the effects of familiarization over 3 sequential testing sessions on EMG test-re-test reliability during both MVICs and SVICs in both resistance-trained and untrained individuals, Frost et al. (2012) found no effect for testing sessions or type of subject on the reliability of the measures taken.

Effect of Visual Feedback

Visual feedback can be provided during SVICs in order to assist in controlling the level of force being produced. When comparing the EMG ICC and COV for both surface and fine wire electrodes in cervical extension between MVICs and SVICs using an isokinetic dynamometer, Burnett et al. (2007) found that visual feedback markedly increased the reliability of the SVIC condition. In addition, Fischer et al. (2010) found similar enhancements in reliability when visual feedback was utilized during MVICs, and it was also found that the feedback increased force production, which suggests that the lower reliability during MVICs may be due to subjects not fully exerting themselves.

References

1. Adams, G. R., Duvoisin, M. R., & Dudley, G. A. (1992). Magnetic resonance imaging and electromyography as indexes of muscle function. *Journal of Applied Physiology*, 73(4), 1578–83.
2. Albertus-Kajee, Y., Tucker, R., Derman, W., & Lambert, M. (2010). Alternative methods of normalising EMG during cycling. *Journal of Electromyography and Kinesiology*, 20(6), 1036-1043.

3. Allen, T. R., Brookham, R. L., Cudlip, A. C., & Dickerson, C. R. (2013). Comparing surface and indwelling electromyographic signals of the supraspinatus and infraspinatus muscles during submaximal axial humeral rotation. *Journal of Electromyography and Kinesiology*, 23(6), 1343-1349.
4. Arabadzhiev, T. I., Dimitrov, V. G., Dimitrova, N. A., & Dimitrov, G. V. (2010). Interpretation of EMG integral or RMS and estimates of “neuromuscular efficiency” can be misleading in fatiguing contraction. *Journal of Electromyography and Kinesiology*, 20(2), 223-232.
5. Arabadzhiev, T. I., Dimitrov, V. G., & Dimitrov, G. V. (2014). The increase in surface EMG could be a misleading measure of neural adaptation during the early gains in strength. *European Journal of Applied Physiology*, 114(8), 1645-1655.
6. 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.
7. Ball, N., & Scurr, J. (2013). Electromyography normalization methods for high velocity muscle actions: Review and recommendations. *Journal of Applied Biomechanics*, 29, 600-608.
8. Balshaw, T. G., & Hunter, A. M. (2012). Evaluation of electromyography normalisation methods for the back squat. *Journal of Electromyography and Kinesiology*, 22(2), 308-319.
9. Beck, T. W., Housh, T. J., Johnson, G. O., Weir, J. P., Cramer, J. T., Coburn, J. W., & Malek, M. H. (2005). The effects of interelectrode distance on electromyographic amplitude and mean power frequency during isokinetic and isometric muscle actions of the biceps brachii. *Journal of Electromyography and Kinesiology*, 15(5), 482-495.

10. Behm, D. G. (1995). Neuromuscular implications and applications of resistance training. *Journal of Strength and Conditioning Research*, 9(4), 264-274.
11. Bigland-Ritchie, B., Johansson, R., Lippold, O. C., & Woods, J. J. (1983). Contractile speed and EMG changes during fatigue of sustained maximal voluntary contractions. *Journal of Neurophysiology*, 50(1), 313-324.
12. Bouisset, S., & Goubel, F. (1971). Interdependence of relations between integrated EMG and diverse biomechanical quantities in normal voluntary movements. *Activitas nervosa superior*.
13. Bouisset, S., & Maton, B. (1972). Quantitative relationship between surface EMG and intramuscular electromyographic activity in voluntary movement. *American Journal of Physical Medicine and Rehabilitation*, 51(6), 285-295.
14. Bouisset, S., & Goubel, F. (1973). Integrated electromyographical activity and muscle work. *Journal of Applied Physiology*, 35(5), 695-702.
15. Brownstein, B. A., Lamb, R. L., & Mangine, R. E. (1985). Quadriceps torque and integrated electromyography*. *Journal of Orthopaedic & Sports Physical Therapy*, 6(6), 309-314.
16. Buckthorpe, M. W., Hannah, R., Pain, T. G., & Folland, J. P. (2012). Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques. *Muscle & Nerve*, 46(4), 566-576.
17. Burden, A. M., Trew, M., & Baltzopoulos, V. (2003). Normalisation of gait EMGs: a re-examination. *Journal of Electromyography and Kinesiology*, 13(6), 519-532.
18. Burden, A. M., "Surface Electromyography", in Payton, C., & Bartlett, R. (Eds.). (2007). *Biomechanical evaluation of movement in sport and exercise: the British Association of Sport and Exercise Sciences guide*. Routledge.

19. Burden, A. (2010). How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25years of research. *Journal of Electromyography and Kinesiology*, 20(6), 1023-1035.
20. Burgar, C. G., Valero-Cuevas, F. J., & Hentz, V. R. (1997). Fine-wire electromyographic recording during force generation: Application to Index Finger Kinesiologic Studies. *American Journal of Physical Medicine and Rehabilitation*, 76(6), 494-501.
21. Burnett, A., Green, J., Netto, K., & Rodrigues, J. (2007). Examination of EMG normalisation methods for the study of the posterior and posterolateral neck muscles in healthy controls. *Journal of Electromyography and Kinesiology*, 17(5), 635-641.
22. Chapman, A. R., Vicenzino, B., Blanch, P., Knox, J. J., & Hodges, P. W. (2010). Intramuscular fine-wire electromyography during cycling: repeatability, normalisation and a comparison to surface electromyography. *Journal of Electromyography and Kinesiology*, 20(1), 108-117.
23. Chowdhury, R. H., Reaz, M. B., Ali, M. A. B. M., Bakar, A. A., Chellappan, K., & Chang, T. G. (2013). Surface electromyography signal processing and classification techniques. *Sensors*, 13(9), 12431-12466.
24. Clancy, E. A., Morin, E. L., & Merletti, R. (2002). Sampling, noise-reduction and amplitude estimation issues in surface electromyography. *Journal of Electromyography and Kinesiology*, 12(1), 1-16.
25. Clarys, J. P. (1994). Electrology and localized electrization revisited. *Journal of Electromyography and Kinesiology*, 4(1), 5-14.
26. Contreras, B., Vigotsky, A. D., Schoenfeld, B. J., Beardsley, C., & Cronin, J. (2015). A comparison of two gluteus maximus EMG maximum voluntary isometric contraction positions. *PeerJ*, 3, e1261.

27. Dankaerts, W., O'Sullivan, P. B., Burnett, A. F., Straker, L. M., & Danneels, L. A. (2004). Reliability of EMG measurements for trunk muscles during maximal and sub-maximal voluntary isometric contractions in healthy controls and CLBP patients. *Journal of Electromyography and Kinesiology*, 14(3), 333-342.
28. De Luca, C. J., & Erim, Z. (1994). Common drive of motor units in regulation of muscle force. *Trends in Neurosciences*, 17(7), 299-305.
29. De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13, 135-163.
30. De Luca, C. J., Gilmore, L. D., Kuznetsov, M., & Roy, S. H. (2010). Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of Biomechanics*, 43(8), 1573-1579.
31. De Luca, C. J., & Contessa, P. (2012). Hierarchical control of motor units in voluntary contractions. *Journal of Neurophysiology*, 107(1), 178-195.
32. Dickx, N., Cagnie, B., Achten, E., Vandemaele, P., Parlevliet, T., & Danneels, L. (2010). Differentiation between deep and superficial fibers of the lumbar multifidus by magnetic resonance imaging. *European Spine Journal*, 19(1), 122-128.
33. Dickx, N., D'Hooge, R., Cagnie, B., Deschepper, E., Verstraete, K., & Danneels, L. (2010). Magnetic resonance imaging and electromyography to measure lumbar back muscle activity. *Spine*, 35(17), E836-42.
34. Dimitrova, N. A., & Dimitrov, G. V. (2003). Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology*, 13(1), 13-36.
35. Disselhorst-Klug, C., Schmitz-Rode, T., & Rau, G. (2009). Surface electromyography and muscle force: limits in sEMG-force relationship and new approaches for applications. *Clinical Biomechanics*, 24(3), 225-235.

36. Duchateau, J., Semmler, J. G., & Enoka, R. M. (2006). Training adaptations in the behavior of human motor units. *Journal of Applied Physiology*, 101(6), 1766-1775.
37. Earp, J. E., Stucchi, D. T., DeMartini, J. K., & Roti, M. W. (2016). Regional surface electromyography of the vastus lateralis during strength & power exercises. *Journal of Strength and Conditioning Research*, Epub ahead of print.
38. Edwards, R. G., & Lippold, O. C. J. (1956). The relation between force and integrated electrical activity in fatigued muscle. *The Journal of Physiology*, 132(3), 677-681.
39. Enoka, R. M., & Duchateau, J. (2015). Inappropriate interpretation of surface EMG signals and muscle fiber characteristics impedes progress on understanding the control of neuromuscular function. *Journal of Applied Physiology*.
40. Ertas, M., Stålberg, E., & Falck, B. (1995). Can the size principle be detected in conventional EMG recordings?. *Muscle & Nerve*, 18(4), 435-439.
41. Farina, D., Merletti, R., & Stegeman, D. F. (2004a). Biophysics of the generation of EMG signals. *Electromyography: physiology, engineering, and noninvasive applications*, 81-105.
42. Farina, D., Merletti, R., & Enoka, R. M. (2004b). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, 96(4), 1486-1495.
43. Farina, D., Holobar, A., Gazzoni, M., Zazula, D., Merletti, R., & Enoka, R. M. (2009). Adjustments differ among low-threshold motor units during intermittent, isometric contractions. *Journal of Neurophysiology*, 101(1), 350-359.
44. Farina, D., Merletti, R., & Enoka, R. M. (2014). The Extraction of Neural Strategies from the Surface EMG: An Update. *Journal of Applied Physiology* (1985).
45. Farina, D., Negro, F., Gazzoni, M., & Enoka, R. M. (2008). Detecting the unique representation of motor-unit action potentials in the surface electromyogram. *Journal of Neurophysiology*, 100(3), 1223-1233.

46. 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.
47. Fauth, M. L., Petushek, E. J., Feldmann, C. R., Hsu, B. E., Garceau, L. R., Lutsch, B. N., & Ebben, W. P. (2010). Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting. *Journal of Strength and Conditioning Research*, 24(4), 1131-1137.
48. Fee, J. W., Miller, F., & Jr. (2012). A Critical Review and Proposed Improvement in the Assessment of Muscle Interactions Using Surface EMG. INTECH Open Access Publisher.
49. Finucane, S. D., Rafeei, T., Kues, J., Lamb, R. L., & Mayhew, T. P. (1998). Reproducibility of electromyographic recordings of submaximal concentric and eccentric muscle contractions in humans. *Electroencephalography and Clinical Neurophysiology*, 109(4), 290.
50. Fischer, S. L., Belbeck, A. L., & Dickerson, C. R. (2010). The influence of providing feedback on force production and within-participant reproducibility during maximal voluntary exertions for the anterior deltoid, middle deltoid, and infraspinatus. *Journal of Electromyography and Kinesiology*, 20(1), 68-75.
51. Frost, L. R., Gerling, M. E., Markic, J. L., & Brown, S. H. (2012). Exploring the effect of repeated-day familiarization on the ability to generate reliable maximum voluntary muscle activation. *Journal of Electromyography and Kinesiology*, 22(6), 886-892.
52. Gabriel, D. A., Kamen, G., & Frost, G. (2006). Neural adaptations to resistive exercise. *Sports Medicine*, 36(2), 133-149.

53. Gazzoni, M., Camelia, F., & Farina, D. (2005). Conduction velocity of quiescent muscle fibers decreases during sustained contraction. *Journal of Neurophysiology*, 94(1), 387-394.
54. Giroux, B., & Lamontagne, M. (1990). Comparisons between surface electrodes and intramuscular wire electrodes in isometric and dynamic conditions. *Electromyography and Clinical Neurophysiology*, 30(7), 397.
55. 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.
56. Goodgold, J. (1977). The motor unit: revisited. *Bulletin of the New York Academy of Medicine*, 53(10), 869-879.
57. 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.
58. Ha, S. M., Cynn, H. S., Kwon, O. Y., Park, K. N., & Kim, G. M. (2013). A Reliability of Electromyographic Normalization Methods for the Infraspinatus Muscle in Healthy Subjects. *Journal of Human Kinetics*, 36, 69-76.
59. Hackett, L., Reed, D., Halaki, M., & Ginn, K. A. (2014). Assessing the validity of surface electromyography for recording muscle activation patterns from serratus anterior. *Journal of Electromyography and Kinesiology*, 24(2), 221-227.
60. Henneman, E., Somjen, G., & Carpenter, D. O. (1965). Functional significance of cell size in spinal motoneurons. *Journal of Neurophysiology*, 28(3), 560-580.
61. Herbert, R. D., & Gandevia, S. C. (1999). Twitch interpolation in human muscles: mechanisms and implications for measurement of voluntary activation. *Journal of Neurophysiology*, 82(5), 2271-2283.

62. Herzog, W., Sokolosky, J., Zhang, Y. T., & Guimarães, A. C. S. (1998). EMG-force relation in dynamically contracting cat plantaris muscle. *Journal of Electromyography and Kinesiology*, 8(3), 147-155.
63. Herzog, W., Powers, K., Johnston, K., & Duvall, M. (2015). A new paradigm for muscle contraction. *Frontiers in Physiology*, 6, 174.
64. Hibbs, A. E., Thompson, K. G., French, D. N., Hodgson, D., & Spears, I. R. (2011). Peak and average rectified EMG measures: Which method of data reduction should be used for assessing core training exercises?. *Journal of Electromyography and Kinesiology*, 21(1), 102-111.
65. Hof, A. L. (1997). The relationship between electromyogram and muscle force. *Sportverletz Sportschaden*, 11(3), 79-86.
66. Hopkins, W. G. (2005). Competitive Performance of Elite Track-and-Field Athletes: Variability and Smallest Worthwhile Enhancements. *Sportscience*.
67. Jacobson, W. C., Gabel, R. H., & Brand, R. A. (1995). Surface vs. fine-wire electrode ensemble-averaged signals during gait. *Journal of Electromyography and Kinesiology*, 5(1), 37-44.
68. Jackson, J. A., O'Brien, N. V., Dempsey, P. G., & Callaghan, J. P. (2008). Comparison of the repeatability of submaximal and maximal methods commonly employed for normalisation of the erector spinae muscles in the thoracic and lumbar region. In *North American Congress on Biomechanics*. Michigan.
69. Jenkins, N. D., Housh, T. J., Bergstrom, H. C., Cochrane, K. C., Hill, E. C., Smith, C. M., & Cramer, J. T. (2015a). Muscle activation during three sets to failure at 80 vs. 30% 1RM resistance exercise. *European Journal of Applied Physiology*, 115(11), 2335-2347.
70. Jenkins, N. D., Housh, T. J., Buckner, S. L., Bergstrom, H. C., Cochrane, K. C., Smith, C. M., & Cramer, J. T. (2015b). Individual Responses for Muscle Activation,

- Repetitions, and Volume during Three Sets to Failure of High-(80% 1RM) versus Low-Load (30% 1RM) Forearm Flexion Resistance Exercise. *Sports*, 3(4), 269-280.
71. Kadaba, M. P., Wootten, M. E., Gainey, J., & Cochran, G. V. (1985). Repeatability of phasic muscle activity: performance of surface and intramuscular wire electrodes in gait analysis. *Journal of Orthopaedic Research*, 3(3), 350.
 72. Kamen, G., & Caldwell, G. E. (1996). Physiology and interpretation of the electromyogram. *Journal of Clinical Neurophysiology*, 13(5), 366-384.
 73. Kendall, F. P., McCreary, E. K., Provance, P. G., Rodgers, M. M., & Romani, W. A. (2005). *Muscles: testing and function with posture and pain*.
 74. Knutson, L. M., Soderberg, G. L., Ballantyne, B. T., & Clarke, W. R. (1994). A study of various normalization procedures for within day electromyographic data. *Journal of Electromyography and Kinesiology*, 4(1), 47.
 75. Kollmitzer, J., Ebenbichler, G. R., & Kopf, A. (1999). Reliability of surface electromyographic measurements. *Clinical Neurophysiology*, 110(4), 725-734.
 76. Komi, P. V., & Buskirk, E. R. (1970). Reproducibility of electromyographic measurements with inserted wire electrodes and surface electrodes. *Electromyography*, 10(4), 357.
 77. Korner, L., Parker, P., Almstrom, C., Andersson, G. B., Herberts, P., Kadefors, R., & Zetterberg, C. (1984). Relation of intramuscular pressure to the force output and myoelectric signal of skeletal muscle. *Journal of Orthopaedic Research*, 2(3), 289-296.
 78. Kuriki, H. U., Mello, E. M., De Azevedo, F. M., Takahashi, L. S. O., Alves, N., & de Faria Negrão Filho, R. (2012). The relationship between electromyography and muscle force. INTECH Open Access Publisher.
 79. Kyröläinen, H., Avela, J., & Komi, P. V. (2005). Changes in muscle activity with increasing running speed. *Journal of Sports Sciences*, 23(10), 1101-1109.

80. Lawrence, J. H., & De Luca, C. J. (1983). Myoelectric signal versus force relationship in different human muscles. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 54(6), 1653-1659.
81. Lehman, G. J., & McGill, S. M. (1999). The importance of normalization in the interpretation of surface electromyography: a proof of principle. *Journal of Manipulative and Physiological Therapeutics*, 22(7), 444.
82. Lehman, G. J. (2002). Clinical considerations in the use of surface electromyography: three experimental studies. *Journal of Manipulative and Physiological Therapeutics*, 25(5), 293-299.
83. Liebenberg, J., Scharf, J., Forrest, D., Dufek, J. S., Masumoto, K., & Mercer, J. A. (2011). Determination of muscle activity during running at reduced body weight. *Journal of Sports Sciences*, 29(2), 207.
84. Lindstedt, S. L., LaStayo, P. C., & Reich, T. E. (2001). When active muscles lengthen: properties and consequences of eccentric contractions. *Physiology*, 16(6), 256-261.
85. Looney, D. P., Kraemer, W. J., Joseph, M. F., Comstock, B. A., Denegar, C. R., Flanagan, S. D., & Maresh, C. M. (2015). Electromyographical and Perceptual Responses to Different Resistance Intensities in a Squat Protocol: Does Performing Sets to Failure With Light Loads Recruit More Motor Units?. *Journal of Strength and Conditioning Research*, Epub ahead of print.
86. Masakado, Y. (1994). Motor unit firing behavior in man. *The Keio Journal of Medicine*, 43(3), 137-142.
87. McGill, S., Juker, D., & Kropf, P. (1996). Appropriately placed surface EMG electrodes reflect deep muscle activity (psoas, quadratus lumborum, abdominal wall) in the lumbar spine. *Journal of Biomechanics*, 29(11), 1503-1507.

88. McGill, S. M., McDermott, A., & Fenwick, C. M. (2009). Comparison of different strongman events: trunk muscle activation and lumbar spine motion, load, and stiffness. *Journal of Strength and Conditioning Research*, 23(4), 1148-1161.
89. Merletti, R., & Di Torino, P. (1999). Standards for reporting EMG data. *Journal of Electromyography and Kinesiology*, 9(1), 3-4.
90. Milner-Brown, H. S., & Stein, R. B. (1975). The relation between the surface electromyogram and muscular force. *Journal of Physiology*, 246(3), 549-569.
91. Mohamed, O., Perry, J., & Hislop, H. (2002). Relationship between wire EMG activity, muscle length, and torque of the hamstrings. *Clinical Biomechanics*, 17(8), 569-579.
92. Moritani, T., Stegeman, D., & Merletti, R. (2004). Basic physiology and biophysics of EMG signal generation. *Electromyography Physiology Engineering and Noninvasive Applications*, 1-20.
93. Onishi, H., Yagi, R., Akasaka, K., Momose, K., Ihashi, K., & Handa, Y. (2000). Relationship between EMG signals and force in human vastus lateralis muscle using multiple bipolar wire electrodes. *Journal of Electromyography and Kinesiology*, 10(1), 59-67.
94. Oskouei, A. H., Paulin, M. G., & Carman, A. B. (2013). Intra-session and inter-day reliability of forearm surface EMG during varying hand grip forces. *Journal of Electromyography and Kinesiology*, 23(1), 216-222.
95. Perry, J., & Bekey, G. A. (1981). EMG-force relationships in skeletal muscle. *Critical Reviews in Biomedical Engineering*, 7(1), 1-22.
96. Perry, J., Easterday, C. S., & Antonelli, D. J. (1981). Surface versus intramuscular electrodes for electromyography of superficial and deep muscles. *Physical Therapy*, 61(1), 7.

97. Rainoldi, A., Galardi, G., Maderna, L., Comi, G., Conte, L. L., & Merletti, R. (1999). Repeatability of surface EMG variables during voluntary isometric contractions of the biceps brachii muscle. *Journal of Electromyography and Kinesiology*, 9(2), 105-119.
98. Rainoldi, A., Bullock-Saxton, J. E., Cavarretta, F., & Hogan, N. (2001). Repeatability of maximal voluntary force and of surface EMG variables during voluntary isometric contraction of quadriceps muscles in healthy subjects. *Journal of Electromyography and Kinesiology*, 11(6), 425.
99. Rajaratnam, BS, Goh, JCH, & Kumar, VP. (2014). A Comparison of EMG Signals from Surface and Fine-Wire Electrodes During Shoulder Abduction. *International Journal of Physical Medicine and Rehabilitation*, 2(206), 2.
100. Rau, G., Schulte, E., & Disselhorst-Klug, C. (2004). From cell to movement: to what answers does EMG really contribute?. *Journal of Electromyography and Kinesiology*, 14(5), 611.
101. Reaz, M. B. I., Hussain, M. S., & Mohd-Yasin, F. (2006). Techniques of EMG signal analysis: detection, processing, classification and applications. *Biological Procedures Online*, 8(1), 11-35.
102. Redfern, M. S., Hughes, R. E., & Chaffin, D. B. (1993). High-pass filtering to remove electrocardiographic interference from torso EMG recordings. *Clinical Biomechanics*, 8(1), 44-48.
103. Rouffet, D. M., & Hautier, C. A. (2008). EMG normalization to study muscle activation in cycling. *Journal of Electromyography and Kinesiology*, 18(5), 866-878.
104. Semciw, A. I., Neate, R., & Pizzari, T. (2014). A comparison of surface and fine wire EMG recordings of gluteus medius during selected maximum isometric

- voluntary contractions of the hip. *Journal of Electromyography and Kinesiology*, 24(6), 835-840.
105. Shield, A., & Zhou, S. (2004). Assessing voluntary muscle activation with the twitch interpolation technique. *Sports Medicine*, 34(4), 253-267.
106. Soderberg, G. L., & Knutson, L. M. (2000). A guide for use and interpretation of kinesiological electromyographic data. *Physical Therapy*, 80(5), 485-498.
107. Solomonow, M., Baratta, R., Shoji, H., & D'ambrosia, R. (1989). The EMG-force relationships of skeletal muscle; dependence on contraction rate, and motor units control strategy. *Electromyography and Clinical Neurophysiology*, 30(3), 141-152.
108. Suzuki, H., Conwit, R. A., Stashuk, D., Santarsiero, L., & Metter, E. J. (2002). Relationships between surface-detected EMG signals and motor unit activation. *Medicine and Science in Sports and Exercise*, 34(9), 1509.
109. Staudenmann, D., Roeleveld, K., Stegeman, D. F., & Van Dieën, J. H. (2010). Methodological aspects of SEMG recordings for force estimation—a tutorial and review. *Journal of Electromyography and Kinesiology*, 20(3), 375-387.
110. Vigotsky, A. D., Beardsley, C., Contreras, B., Steele, J., Ogborn, D., & Phillips, S. M. (2015a). Greater electromyographic responses do not imply greater motor unit recruitment and 'hypertrophic potential' cannot be inferred. *Journal of Strength and Conditioning Research*, Epub ahead of print.
111. Vigotsky, A. D., Ogborn, D., & Phillips, S. M. (2015b). Motor unit recruitment cannot be inferred from surface EMG amplitude and basic reporting standards must be adhered to. *European Journal of Applied Physiology*.
112. Waite, D. L., Brookham, R. L., & Dickerson, C. R. (2010). On the suitability of using surface electrode placements to estimate muscle activity of the rotator cuff as

- recorded by intramuscular electrodes. *Journal of Electromyography and Kinesiology*, 20(5), 903-911.
113. Wakahara, T., Fukutani, A., Kawakami, Y., & Yanai, T. (2013). Nonuniform muscle hypertrophy: its relation to muscle activation in training session. *Medicine and Science in Sports and Exercise*, 45(11), 2158–65.
 114. Wakahara, T., Miyamoto, N., Sugisaki, N., Murata, K., Kanehisa, H., Kawakami, Y. & Yanai, T. (2012). Association between regional differences in muscle activation in one session of resistance exercise and in muscle hypertrophy after resistance training. *European Journal of Applied Physiology*, 112(4), 1569–76.
 115. Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*, 19(1), 231-240.
 116. Winter, D. A., Fuglevand, A. J., & Archer, S. E. (1994). Crosstalk in surface electromyography: theoretical and practical estimates. *Journal of Electromyography and Kinesiology*, 4(1), 15-26.
 117. Yang, J. F., & Winter, D. A. (1983). Electromyography reliability in maximal and submaximal isometric contractions. *Archives of Physical Medicine and Rehabilitation*, 64(9), 417-420.
 118. Zakaria, D., Kramer, J. F., & Harburn, K. L. (1996). Reliability of non-normalized and normalized integrated EMG during maximal isometric contractions in females. *Journal of Electromyography and Kinesiology*, 6(2), 129.
 119. Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. *European Journal of Applied Physiology and Occupational Physiology*, 50(1), 41-54.