An Analysis of High-Bar and Low-Bar Back-Squat Techniques in Olympic Weightlifters and Powerlifters

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Thesis Abstract

The barbell back-squat is one of the most common exercises in strength and conditioning practice; especially in Olympic weightlifting and powerlifting. There are two main bar placements within the back-squat; the high-bar and low-bar positions. The high-bar position, favoured by Olympic weightlifters, closely resembles the upright body position of the two competition lifts of the sport; the snatch and clean and jerk. The low-bar position, favoured by powerlifters, typically allows greater loads to be lifted by utilising the posterior-chain musculature during the back-squat (one of the three competition lifts in the sport). Unfortunately, little research exists comparing the high-bar back-squat with the low-bar back-squat, and no research has examined either lift above 90% of one repetition maximum. Furthermore, no authors have biomechanically compared the high-bar back-squat to the Olympic lifts (e.g. snatch and clean and jerk). The aims of this thesis were to (1) review the current literature and quantitatively assess the kinetic and kinematic findings among the limited research; (2) compare and contrast the high-bar back-squat and low-bar back-squat up to maximal effort; and (3) assess the differences and/or similarities between the high-bar back-squat and the Olympic lifts. Through an extensive literature review, the high-bar back-squat was found to commonly present a larger hip angle, smaller knee angle and equivalent ankle angle compared to the low-bar back-squat; inferring the high-bar placement creates a more upright truck position for the lifter and requires more quadriceps muscle activation. Experimentally, these findings were confirmed with the high-bar back-squat producing larger hip angles and smaller knee angles compared to the powerlifters (16–21% larger and 10–12% smaller, respectively) and low-bar controls (16–21% larger and 10–12% smaller, respectively). While the Olympic weightlifters and powerlifters lifted similar relative loads, the low-bar controls were able to lift 2.5–5.2% larger relative loads compared to the high-bar controls. As expected, the high-bar back-squat also showed similar kinematics to the snatch and the clean but substantially different kinetics across all loads lifted. Performing a back-squat with a low-bar placement, situates the lifter (advanced and recreational) in a stronger position to lift larger loads compared to the high-bar placement. The establishment of a more advantageous kinematic posture during the low-bar back-squat could potentially maximise the utilisation of the stronger posterior hip musculature thus increasing the stability and moment arm at the hip. The low-bar back-squat therefore appears to provide the best chance of lifting the largest relative load. The kinematic similarities in posture between the high-bar back-squat and the Olympic lifts suggests the potential of similar trunk, hip and thigh muscular activity of key stabilising muscles and repetitive positional alignment in the

"catch" position. The differing kinetics however, are more likely due to technical differences between the high-bar back-squat, snatch and clean; wherein the Olympic lifts require additional elements of upper-body strength and stability. The high-bar back-squat does appear to yield an efficient carryover to the Olympic lifts as a suitable supplementary exercise; provided the technical components of the lifts are maintained.

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DECLARATION

I hereby declare that this 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 explicitly 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.

Signed: 

Date: 4 March 2016

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LIST OF ABBREVIATIONS

BBS	Barbell Back-Squat
HBBS	High-Bar Back-Squat
LBBS	Low-Bar Back-Squat
GRF	Ground Reaction Forces
EMG	Electromyography
OLY	Olympic weightlifters
POW	Powerlifters
HBCON	Control high-bar back-squat
LBCON	Control low-bar back-squat
F_v	Vertical ground reaction force
RFD	Rate of force development

CHAPTER ONE - Introduction

In current strength and conditioning practice, the barbell back-squat (BBS) is widely used. In terms of sports specific lower body movements many sport scientists and coaches alike regard the BBS as fundamental for the assessment and improvement of lower limb strength and function (Comfort, Stewart, Bloom, & Clarkson, 2014; Cormie, McCaulley, Triplett, & McBride, 2007; Cormie, McGuigan, & Newton, 2010b; Escamilla, 2001; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; McCaw & Melrose, 1999; Senter & Hame, 2006; Sleivert & Taingahue, 2004; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). The BBS itself is most commonly performed with a "high bar" placement on the upper trapezius and shoulders. However, it can also be performed with a "low bar" placement on the posterior aspects of the shoulders and lower trapezius. A number of strength and conditioning research studies have been conducted examining the BBS with both the high-bar back-squat (HBBS), and low-bar back-squat (LBBS) variations (Anderson, Courtney, & Casmeli, 1998; Escamilla, 2001; Gullett, Tillman, Gutierrez, & Chow, 2009; Hales, Johnson, & Johnson, 2009; Lander, Bates, & Devita, 1986; McCaw & Melrose, 1999; Pincivero, Aldworth, Dickerson, Petry, & Shultz, 2000; Salem, Salinas, & Harding, 2003; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). However, only five authors have specifically compared the HBBS and LBBS in terms of kinetics, kinematics and/or muscular activity (Benz, 1989; Fry, Aro, Bauer, & Kraemer, 1993; Goodin, 2015; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; Wretenberg, Feng, & Arborelius, 1996). Moreover, the HBBS is associated specifically with sports such as Olympic weightlifting, where it is incorporated as an accessory movement to the two competition lifts; the snatch and the clean and jerk (Wretenberg, Feng, & Arborelius, 1996). In comparison, the LBBS is thought to allow for a greater weight to be lifted and is commonly used by competitive powerlifters as the BBS is one of the powerlifting competition lifts (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012).

The difference in bar position between the HBBS and LBBS (Figure 1) result in kinematic changes to the joint angles of the three key joints; the hip, knee and ankle joints, throughout the squat. There is also a resultant shortening of the trunk lever arm of the LBBS in comparison to the HBBS. These variations result from a change in the centre of mass (COM) of the system, and the strategies employed by the lifter to ensure the COM remains in their base of support (BOS) for balance. The joint angle and lever arm differences between the HBBS and LBBS manifest as greater forward trunk lean and smaller trunk inclination angles at the hip joint (Benz, 1989; Fry, Aro, Bauer, & Kraemer, 1993; Wretenberg, Feng, & Arborelius, 1996), a more vertical shank segment (i.e. a larger joint angle) at the ankle joint (Fry, Aro, Bauer, & Kraemer, 1993), and smaller flexion angles at the knee joint (Wretenberg, Feng, & Arborelius, 1996). The differences in bar position, and resultant changes in joint angles and trunk lever arm also serve to create differences in the activation patterns of key muscles throughout the movement, as the weight is transferred differently. This transfer of weight however does not result in statistically significant changes in ground reaction forces (GRF), or in vertical and horizontal bar displacement (Goodin, 2015), as may be expected between the LBBS and HBBS, as a result the mechanical differences in trunk lever arm length.

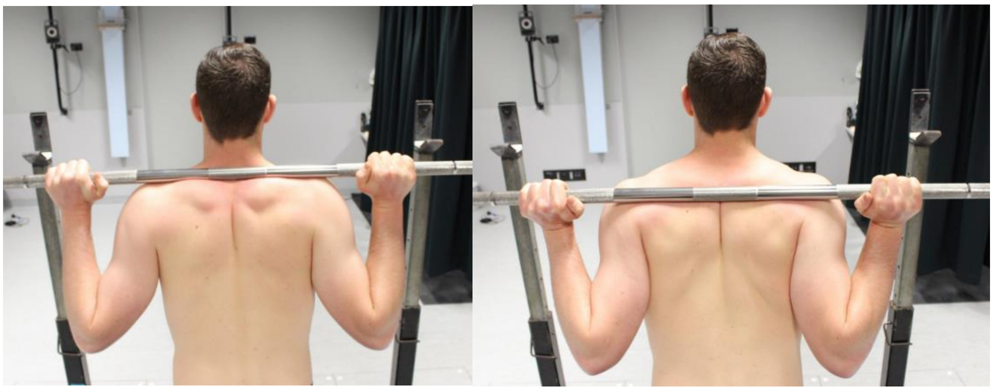


Figure 1: Schematic representation of two variations of the barbell back-squat.

At present, a comparison of the kinetics and kinematics of both BBS's has not been completed above 90% 1RM. Further work must be done in order to fully understand the kinematic and kinetic differences between the HBBS and LBBS up to and including a maximal effort. The differences in joint angles, force production and GRF will be discussed, and a full understanding of the two styles of the BBS created. This will then allow for educated decisions to be made by practitioners with regards to exercise prescription and the optimal style of BBS for sport specific applications.

Furthermore, in the current strength and conditioning literature there have been no studies comparing the performance of the HBBS, typically used by Olympic weightlifters, with the performance of the two Olympic weightlifting competition lifts: the snatch and clean and jerk. Therefore, this thesis compared the snatch and clean to the HBBS, using the same kinetic and kinematic outcomes as used to compare the HBBS to LBBS. Comparing and contrasting these three movements creates a greater level of understanding of each lifts relationship to the others. Additionally, by comparing the relationship in the load lifted during each movement and Olympic weightlifter's ability to perform the competition lifts could potentially be predicted through analysis of the HBBS.

Purpose Statement

Currently, the kinetic and kinematic differences between HBBS and LBBS beyond 90% 1RM are unknown. Additionally, a comparison between the HBBS and the Olympic weightlifting competition lifts has not been performed. Therefore, the purpose of this thesis is to build on the limited research in the field at present. The results of this investigation will add to the current body of knowledge of Olympic weightlifting and powerlifting athletes alike, and aid in exercise prescription.

Thesis Aims

1. Review the published literature to determine the current uses and effects of the HBBS and LBBS exercises.
2. Compare and contrast the HBBS and LBBS exercises, in terms of kinematics and kinetics.
3. Compare and contrast the performance of a HBBS to the performance of the snatch and clean, in terms of kinematics and kinetics, in Olympic weightlifters.

Study Limitations

1. There was no crossover of the back-squat exercises between the Olympic weightlifters (who only performed the HBBS), and the powerlifters (who only performed the LBBS). The control group was the only cohort to perform both back-squat variations.
2. Due to feasibility issues, two different force platforms had to be used to test the Olympic weightlifting competition lifts (the snatch and the clean and jerk), and the back-squats.
3. Participants were recruited from a number of different clubs/gyms and as such the participants were from different training backgrounds and were at different stages of preparation for upcoming competitions.
4. The control group performed maximal tests of both the HBBS and LBBS in a single testing session. Therefore, a resultant level of fatigue may have affected the performance of the second squat variation in this testing session. This fatigue effect was minimised by randomising the order that each participant performed the HBBS and LBBS. Three participants performed the HBBS first, and LBBS second, while the remaining three participants performed them in the opposite order.
5. Ideally, kinematic, kinetic and electromyographic (EMG) data would have been presented to create a full and extensive profile of each lift type. EMG was collected

with surface electrodes placed on the muscle belly of 1) the gastrocnemius medial head; 2) biceps femoris; 3) gluteus maximus; 4) erector spinae longissimus; 5) vastus medalis; 6) adductor magnus; 7) rectus femoris; and 8) rectus abdominis for each participant. However, in order to finish the thesis on time, and not exceed the appropriate length and scope of a Master's thesis, the EMG data has not been included or analysed. In future, this data will be used to create further publications.

Study Delimitations

1. Competitive sub-elite Olympic weightlifters, and powerlifters were chosen as the test populations for this thesis. We chose this level of athlete to ensure expertise in each of the tested movements, whilst ensuring the finding of the thesis are applicable to a wide range of skill levels.
2. Athletes were included if currently in a general strength phase of training, as opposed to immediate competition preparation. This increased the adherence of the participants and allowed a level of flexibility within their training programmes to incorporate the extra volume arising from the testing sessions.
3. Two different force plates were used to record the squat versus snatch and clean and jerk trials. All squat trials were completed on two embedded force platforms (Model AM6501, Bertec Corp., Columbus, Ohio, USA), in order to collect data for future research into asymmetries between legs. Conversely, all snatch and clean and jerk trials were performed on a separate single force platform (Model ACP, Advanced Mechanical Technology, Inc., Watertown, Massachusetts, USA). During pilot testing, snatch and clean and jerk attempts were performed with two spotters present to help assist with the lowering of overhead loads which could not be dropped directly onto the laboratory floor. However, this became impractical due to the large loads that were being lifted overhead, so it was deemed that a weightlifting platform had to be built around a force plate to enable the lifters to drop the loads (in a controlled fashion) from an overhead position (as done in training). This platform was raised off the ground, and therefore the embedded Bertec force plates in the laboratory were not practical. Instead, a separate plate (Model ACP, Advanced Mechanical Technology, Inc., Watertown, Massachusetts, USA) that could be embedded in the platform itself was warranted. Pilot testing determined both force plates to be reliable and accurate.

Thesis Format

This thesis is presented in a pathway two format. As such, it comprises of a series of chapters, with a narrative review, two articles in different stages of review, and a general discussion/ summary chapter.

Chapter two is a narrative review that specifically focuses on the HBBS and LBBS. This review discusses the current and prior research pertaining to the analysis of HBBS and LBBS in Olympic weightlifters and powerlifters in terms of each movement's kinematics, kinetics and muscular activity.

Chapter three focuses on comparing and contrasting the HBBS and LBBS, in terms of kinematics and kinetics. Chapter four then focuses on comparing performance of a HBBS and the performance of the snatch and clean in Olympic weightlifters.

The fifth and final chapter is a summary chapter, in which the overall findings of the data presented in chapters three and four, with support from previous research presented in chapter two, are discussed. This chapter also outlines the practical applications and limitations of our current research along with proposing potential areas for future research.

It should be noted that within the series of chapters, three stand-alone publications are presented and therefore due to the chosen submission format, there may be some unavoidable repetition.

The author contributions to the papers are as follows:

A review of kinetic, kinematic and muscle activity studies of the high-bar back-squat and low-bar back-squat.

Glassbrook, D., (80%), Brown, S. R., (5%), Helms, E., (5%), Storey, A., (10%).

The high-bar and low-bar back-squat: A kinematic and kinetic analysis.

Glassbrook, D., (80%), Brown, S. R., (5%), Helms, E., (5%), Storey, A., (10%).

The high-bar back-squat and Olympic weightlifting snatch, and clean: A kinematic and kinetic comparison.

Glassbrook, D., (80%), Brown, S. R., (5%), Helms, E., (5%), Storey, A., (10%).

Dr Adam Storey

Scott R. Brown

Eric Helms

Ethical approval for this research was approved by the Auckland University of Technology Ethics Committee on the 19th of November 2015, with the reference 14/398.

CHAPTER TWO - A review of kinetic, kinematic and muscle activity studies of the high-bar back-squat and low-bar back-squat

Preface

This chapter is an extensive review of the current literature pertaining to the kinematic, kinetic and muscle activity differences between the HBBS and LBBS. The purpose of this review was to provide a full background to the subsequent chapters, and create an understanding of why the LBBS typically allows greater loads to be lifted.

Introduction

The squat is one of the most prevalent exercises in strength and conditioning, and is commonly used as a training stimulus for a variety of different sports. Strength and power athletes such as Olympic weightlifters and powerlifters, as well as endurance and team sports athletes all routinely incorporate the squat into their training practices (Dintiman & Ward, 2003; Gamble, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). Moreover, the squat is widely regarded as not only a fundamental measure of lower limb and trunk strength and function, but also a means of increasing the maximal strength of the lower limbs (Comfort, Stewart, Bloom, & Clarkson, 2014; Cormie, McCaulley, & McBride, 2007; Cormie, McCaulley, Triplett, & McBride, 2007; Cormie, McGuigan, & Newton, 2010a, 2010b; Escamilla, 2001; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; McCaw & Melrose, 1999; Senter & Hame, 2006; Sleivert & Taingahue, 2004; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). In essence, the squat is a simple movement, which starts with the individual in an upright position, where the knees and hip are near full extension. Once stable, the individual then lowers their hips towards the ground, until a desired depth is reached, and then in a continuous motion the individual ascends back up to the upright position (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). Squats are typically performed in two ways, as a front-squat (FS) where a barbell is placed anteriorly on the shoulder, and the BBS where the barbell is placed posteriorly to the shoulder, across the trapezius musculature (Gullett, Tillman, Gutierrez, & Chow, 2009).

This review will focus on the barbell back-squat (BBS), and specifically the two different barbell positional variations of the BBS; the traditional "high-bar" back-squat (HBBS) and the "low-bar" back-squat (LBBS). During the traditional HBBS the bar is placed across the top of the trapezius, just below the spinous process of the C7 vertebra. This exercise is commonly used by Olympic weightlifters to simulate the catch position of the Olympic weightlifting competition lifts; the snatch and clean and jerk (Wretenberg, Feng, & Arborelius, 1996). Conversely, the LBBS places the bar on the lower trapezius, just over the posterior deltoid, along the spine of the scapula (Wretenberg, Feng, & Arborelius, 1996), and is most commonly used in competitive powerlifting (where the BBS is one of the three competition lifts), as it is thought to enable higher loads to be lifted (O'Shea, 1985). In competitive powerlifting, there are regulations that each lifter must comply with in order for each lift to count towards their total (International Powerlifting Federation, 2015). One such regulation pertaining to the BBS, is that sufficient 'depth' must be reached. That is, there must be sufficient flexion of the knees and lowering of the hips towards the ground, so that "the top surface of the legs at the hip joint are lower than the top of the knees" (International Powerlifting Federation, 2015). As a result, it is common for powerlifters to replicate this required depth in training. In Olympic weightlifting, the BBS is not a competition lift, and therefore, in training BBS depth is commonly modelled the catch position of the snatch and clean and jerk. This often manifests as a deeper BBS, with greater flexion at the knee and ankle.

The BBS is a closed kinetic chain exercise (CKE), as the feet are anchored to the ground throughout its performance (Escamilla et al., 1998; Steindler, 1955; Stone et al., 2000). This is in comparison to an open chain kinetic exercise (OKC), were peripheral segments are allowed to move in free space (such as the leg extension exercise). The BBS requires flexibility and range of motion at the hip, knee and ankle joints. Furthermore, the HBBS and LBBS require different levels of flexibility at each of these three joints, as indicated earlier by the different requirements in depth and bar position. These three joints are known as the lower extremity kinetic chain, and are recruited in unison in the CKC BBS movement, in comparison to an OKC movement such as the leg extension, which only isolates one or two joints of the chain (Palmitier, An, Scott, & Chao, 1991). As such, the BBS is also commonly referred to as a compound exercise, and not an isolation exercise. The BBS relies on the co-activation of a large number of muscles across the lower extremity kinetic chain to complete the action. Instability exists in three planes of motion, and therefore, force is also produced and applied across three planes of motion (Kawamori & Haff, 2004). The CKC nature of the BBS also ensures that the movement utilises each joint in coordination with one another, and a larger muscle mass than OKC exercises. In fact, it is predicted that over 200 muscles of the lower limb and trunk are active during the squat, as a means to provide movement in both concentric and eccentric portions and to provide overall stability via isometric contractions (Nisell & Ekholm, 1986; Stoppani, 2006). Furthermore, CKC exercises tend to ensure a higher degree of joint motion, an increase in muscle recruitment and are therefore thought to replicate functional and athletic tasks better than OKC exercises (Renström, Arms, Stanwyck, Johnson, & Pope, 1986; Schoenfeld, 2010; Shelbourne, Klootwyk, & DeCarlo, 1992; Steinkamp, Dillingham, Markel, Hill, & Kaufman, 1993; Yack, Collins, & Whieldon, 1993). The BBS is traditionally performed with a free-weight; however, there are variations of the squat that rely on the structure of a machine or rack such as the smith machine. This external structure constrains the movement so that the bar can only travel up and down in a straight line, thus reducing the demands on the squat-specific muscles, which might potentially dampen the stabilization stimulus and specificity to sport (Schwanbeck, Chilibeck, & Binsted, 2009).

The LBBS is thought to allow for a larger weight to be lifted than the HBBS (O'Shea, 1985). As such, competitive powerlifters commonly use the LBBS, where the goal of this sport is to lift the greatest load possible. The purpose of this review is to provide a summary of prior kinematic, kinetic, and muscle activity research on the HBBS and LBBS, to create an understanding of why the LBBS might allow greater load to be lifted. Specifically, joint angles (Figure 2), vertical ground reaction forces (F_v), and muscle activity will be the focus of discussion. This review will present current literature in each of these categories for both the HBBS, and LBBS, and allow educated decisions to be made by practitioners concerning exercise prescription and the optimal style of BBS for different sport specific applications.

Methods

Definition of Terms

Many authors examining the squat use different terminology when describing the study's experimental procedures. Therefore, definitions of these terms are vital to the clarity of this review. Where authors did not use the same definitions for variables, their raw data was requested, and used to derive the variables as defined in our review. A 'high-bar' squat is synonymous with the 'traditional' squat and 'Olympic' squat, while a 'low-bar' squat is synonymous with a 'powerlifting' squat. A 'squat' is synonymous with a BBS and was not confused or compared with other squat variations that use different bar positions or loading modalities. An analysis of squat styles besides HBBS and LBBS is outside of the scope of this review, but for more information on other squat styles, the reader is referred to texts by Delavier (2010) and Newton (2002).

Search Parameters and Criteria

PubMed, SPORTDiscus, and Google Scholar electronic databases were searched online up to January 2016. The employed search strategy limited database results to academic journals, reviews, dissertations and human subjects when applicable. Keywords were arranged to include either squat*, high-bar*, low-bar* OR back squat*, AND weightlifting*, Olympic weightlifting*, Olympic*, powerlifting*, or lifting*. Inclusion criteria for this review comprised articles that included (i) healthy; (ii) resistance-trained (≥ 6-month experience); (iii) adults (≥ 18 years); and (iv) provided one of the following variables: hip, knee or ankle joint angles, GRFs, impulse, rate of force development (RFD), power and/or lower extremity EMG during a squat.

Articles were excluded if 1) they were not available in English and not previously referred to by other sources; 2) the full text was not available; 3) male and female subjects were not separated; or 4) comprised a case study, a poorly designed cohort/case-control study, anecdotal evidence, animal research, bench research or unpublished clinical observations (i.e. levels of clinical evidence and study design consisting of a score of 4 or 5 as adapted from the Oxford Centre for Evidence-Based Medicine) (Medina, McKeon, & Hertel, 2006) (Figure 3). Only full text sources were included so that methodology detail could be assessed. Finally, a comprehensive search of article reference lists and citation tracking on Google Scholar were used to identify any additional relevant articles.

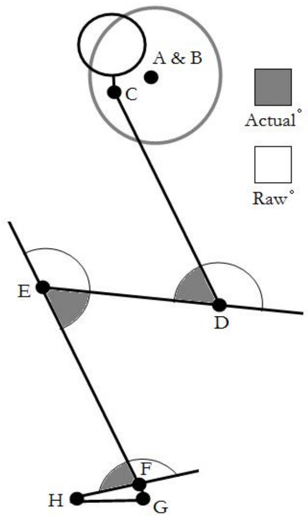


Figure 2: Actual and Raw joint angles of the hip, knee and ankle. Taken from A) the left end of the barbell, B) the right end of the barbell, C) acromion process, D) greater trochanter, E) lateral epicondyle of the femur, F) lateral malleolus, G) the top of the heal lift of the lifting shoe, and H) the base of the fifth metatarsal.

Findings: Kinematics

Hip

The BBS is performed by the simultaneous flexion or extension of three key joints; the hip, knee and ankle, known as the lower extremity kinetic chain (Palmitier, An, Scott, & Chao, 1991). The hip joint connects the trunk segment of the body to the thigh segment of the lower limb. The resultant angle between the segments; the hip angle is synonymous with the names trunk and torso angle. A difference in trunk angle manifests as either a greater forward lean (i.e. a reduced trunk angle), or a more upright orientation of the torso (i.e. an increased trunk angle). Prior research specifically comparing the HBBS to the LBBS has shown that

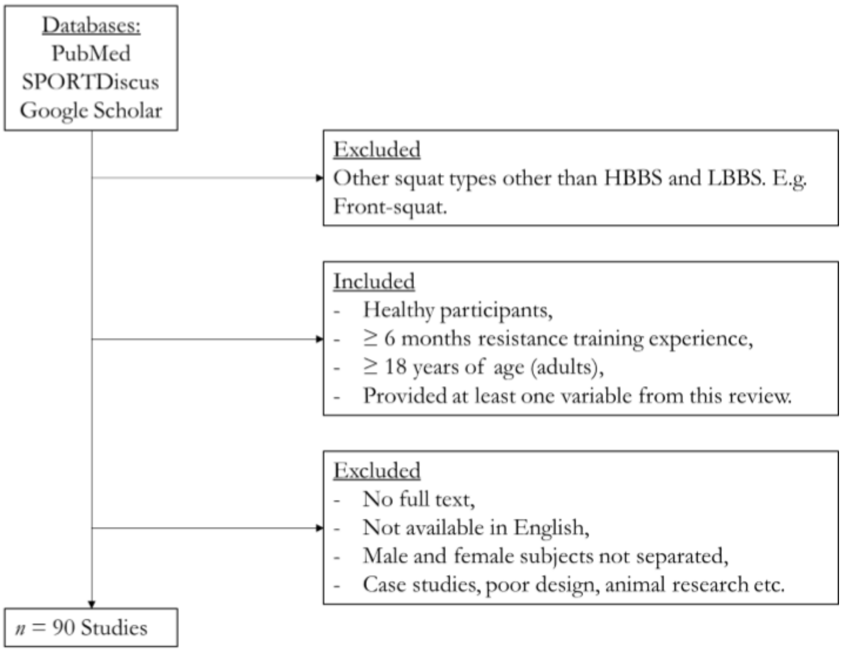


Figure 3: Study exclusion and inclusion process.

the LBBS is defined by a smaller absolute trunk angle, and therefore greater forward lean (Benz, 1989; Fry, Aro, Bauer, & Kraemer, 1993; Wretenberg, Feng, & Arborelius, 1996). This forward lean, effectively maximises the posterior displacement of the hip, and therefore increases the force placed on the hip, in comparison to the knee joint. This results in a decreased moment arm when placing the bar lower on the back, and there is also an increase in stability and potential decrease in stress placed on the lumbar region, and at the ankle, when compared to the HBBS (Sato, Fortenbaugh, & Hydock, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). These factors may contribute to understanding why the LBBS might allow for greater loads to be lifted. However, these joint angle results are not definitive, and there are mixed results in the literature for the size of HBBS and LBBS trunk angles at peak hip flexion (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2001; Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Hooper et al., 2014; Kobayashi et al., 2010; McKean, Dunn, & Burkett, 2010; McLaughlin, Dillman, & Lardner, 1977; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012) (Tables 1 and 2). Lastly, it is common for Olympic weightlifters and powerlifters to wear special weightlifting/squat shoes/boots when performing the BBS (International Weightlifting Federation, 2015; Sato, Fortenbaugh, & Hydock, 2012; Sato, Fortenbaugh, Hydock, & Heise, 2013). These shoes are characterised by designs incorporating a raised heel, usually of ~2.5 cm in height, and stiff non-compressible soles, with a reinforced outer sole. The raised heel present in weightlifting shoes, and also in running shoes when compared to barefoot, has been shown to reduce overall trunk lean during the BBS (Sato, Fortenbaugh, & Hydock, 2012; Sato, Fortenbaugh, Hydock, & Heise, 2013).

Table 1: High-bar back-squat peak hip flexion

Reference	Athletes (*n*) and gender	Sport	Conditions	Load (kg/%RM)	Angle (°)	Significance (p)
(Flanagan & Salem, 2007)	9 M & 9 F	Experienced recreational lifters	LHS	25% 1RM	87 ± 7	
			RHS	25% 1RM	87 ± 8	
			LHS	50% 1RM	85 ± 7	
			RHS	50% 1RM	85 ± 7	
			LHS	75% 1RM	84 ± 7	
			RHS	75% 1RM	85 ± 7	
			LHS	100% 1RM	83 ± 7	
			RHS	100% 1RM	83 ± 7	
(Donnelly, Berg, & Fiske, 2006)	10 M	University gridiron	Downward gaze	25% 1RM	77 ± 7	0.05
			Straight gaze	25% 1RM	84 ± 15	0.05
			Upward gaze	25% 1RM	86 ± 14	0.05
(Hooper et al., 2014)	12 M & 13 F	Experienced recreational lifters	Beginning	75% 1RM	87 ± 16	0.016
			Fatigued	75% 1RM	117 ± 73	0.016
(Kobayashi et al., 2010)	18 M	University long jump	Take off leg	50% 3RM	97 ± 9	< 0.05
			Non-take off leg	50% 3RM	99 ± 8	
			Take off leg	70% 3RM	95 ± 10	< 0.05
			Non-take off leg	70% 3RM	97 ± 10	
			Take off leg	90% 3RM	94 ± 11	< 0.05
			Non-take off leg	90% 3RM	97 ± 10	
(McKean, Dunn, & Burkett, 2010)	16 M	Experienced recreational lifters		BW	78 ± 3	< 0.05
				BW + 50%	74 ± 4	< 0.05
(Fry, Aro, Bauer, & Kraemer, 1993)	6 M	Olympic weightlifting and powerlifting	Segment angle	50% 1RM	46 ± 5	
(Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012)	12 M	Powerlifting	Traditional squat	30, 50 & 70% 1RM	104 ± 5	< 0.05

M, Male; F, Female; RHS, Right hand side; LHS, Left hand side; 1RM, One repetition maximum; 3RM, Three repetition maximum; BW, Body weight. All angle data presented as mean ± standard deviation.

Table 2: Low-bar back-squat peak hip flexion

Reference	Athletes (*n*) and gender	Sport	Conditions	Load (%RM)	Angle (°)	Significance (p)
(McLaughlin, Dillman, & Lardner, 1977)	32 M	Powerlifting	Highly skilled	100% 1RM	42 ± 3	
			Low skill level	100% 1RM	39 ± 3	
(Escamilla et al., 2001)	39 M	Powerlifting	Narrow stance	100% 12RM	107 ± 10	
			Medium stance	100% 12RM	109 ± 8	
			Wide stance	100% 12RM	110 ± 7	
(Hales, Johnson, & Johnson, 2009)	25 M	Powerlifting	Begin of ascent	100% 1RM	58 ± 8	< 0.01
(Fry, Aro, Bauer, & Kraemer, 1993)	6 M	Olympic weightlifting and powerlifting	Segment angle	50% 1RM	41 ± 6	
(Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012)	12 M	Powerlifting	Traditional squat	30, 50 & 70% 1RM	113 ± 6	< 0.05

M, Male; F, Female. All angle data presented as mean ± standard deviation.

Knee

The knee joint connects the thigh segment of the lower limb to the shank segment. There are apparent differences in knee joint angle between the HBBS and LBBS, resulting from differences in required depths, as alluded to earlier in this review. Anecdotally the HBBS can be defined as a "deeper squat", with greater knee flexion at maximum depth (70-90°), in comparison to the LBBS (100-120°) (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2001; Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Han, Ge, Liu, & Liu, 2013; Hooper et al., 2014; Kobayashi et al., 2010; McKean, Dunn, & Burkett, 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; van den Tillaar, Andersen, & Saeterbakken, 2014) (Tables 3 and 4). However, there are some studies which have reported the reverse (Hales, Johnson, & Johnson, 2009; Kobayashi et al., 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). This may have resulted from the experience of the participants in the case of Kobayashi et al. (2010) and Hales et al. (2009), and the fact that Swinton et al., (2012) had only powerlifters complete the HBBS and LBBS.

Ankle

Lastly, the ankle joint connects the shank segment of the lower limb to the foot segment. Currently, only five studies have recorded ankle joint angle data, three of which from the HBBS only (Flanagan & Salem, 2007; Kobayashi et al., 2010; Sato, Fortenbaugh, & Hydock, 2012), one from the LBBS only (Hales, Johnson, & Johnson, 2009) and one from both the HBBS and LBBS (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). One study also looked at the ankle segment angle in Olympic weightlifters and powerlifters (Fry, Aro, Bauer, & Kraemer, 1993). These studies show similar results for the HBBS ankle joint angle across studies, however there are mixed results for the LBBS (Tables 5 and 6). Further research is warranted to provide definitive differences between the HBBS and LBBS.

Table 3: Low-bar back-squat peak knee flexion

Reference	Athletes (*n*) and gender	Sport	Conditions	Load (%RM)	Angle (°)	Significance (p)
(Escamilla et al., 2001)	39 M	Powerlifting	Narrow stance	100% 12RM	106 ± 8	
			Medium stance	100% 12RM	102 ± 7	
			Wide stance	100% 12RM	99 ± 10	
(Hales, Johnson, & Johnson, 2009)	25 M	Powerlifting	Begin of ascent	100% 1RM	66 ± 7	
(Fry, Aro, Bauer, & Kraemer, 1993)	6 M	Olympic weightlifting and powerlifting	Segment angle	50% 1RM	68 ± 14	
(Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012)	12 M	Powerlifting	Traditional squat	30, 50 & 70% 1RM	112 ± 4	< 0.05

M, Male; F, Female. All angle data presented as mean ± standard deviation.

Table 4: High-bar back-squat peak knee flexion

Reference	Athletes (*n*) and gender	Sport	Conditions	Load (%RM)	Angle (°)	Significance (p)
(Flanagan & Salem, 2007)	9 M & 9 F	Experienced recreational lifters	LHS	25% 1RM	85 ± 6	
			RHS	25% 1RM	85 ± 6	
			LHS	50% 1RM	83 ± 5	
			RHS	50% 1RM	84 ± 5	
			LHS	75% 1RM	81 ± 5	
			RHS	75% 1RM	83 ± 5	
			LHS	100% 1RM	80 ± 7	
			RHS	100% 1RM	82 ± 6	
(Donnelly, Berg, & Fiske, 2006)	10 M	University gridiron	Downward gaze	25% 1RM	82 ± 11	
			Straight gaze	25% 1RM	83 ± 12	
			Upward gaze	25% 1RM	85 ± 12	
(Hooper et al., 2014)	12 M & 13 F	Experienced recreational lifters	Beginning	75% 1RM	97 ± 7	0.016
			Fatigued	75% 1RM	90 ± 6	0.016
(Kobayashi et al., 2010)	18 M	University long jump	Take off leg	50% 3RM	109 ± 10	
			Non-take off leg	50% 3RM	110 ± 10	
			Take off leg	70% 3RM	107 ± 12	
			Non-take off leg	70% 3RM	108 ± 12	
			Take off leg	90% 3RM	104 ± 11	
			Non-take off leg	90% 3RM	105 ± 10	
(McKean, Dunn, & Burkett, 2010)	16 M	Experienced recreational lifters		BW	65 ± 2	< 0.05
				BW + 50%	59 ± 2	< 0.05
(Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012)	12 M	Powerlifting	Traditional squat	30, 50 & 70% 1RM	121 ± 3	< 0.05
(Han, Ge, Liu, & Liu, 2013)	9 M & 9 F	N/A	Neutral squat	BW	94 ± 11	
			Squeeze squat	BW	89 ± 13	
			Outward squat	BW	92 ± 14	
(Fry, Aro, Bauer, & Kraemer, 1993)	6 M	Olympic weightlifting and powerlifting	Segment angle	50% 1RM	63 ± 12	
(van den Tillaar, Andersen, & Saeterbakken, 2014)	15 M	Experienced recreational lifters	Lowest barbell point	95% 6RM	89 ± 12	

M, Male; F, Female; RHS, Right hand side; LHS, Left hand side; 1RM, One repetition maximum; 3RM, Three repetition maximum; PT, Personal trainer; BW, Body weight; N/A, Not applicable.
All angle data presented as mean ± standard deviation.

Table 5: Low-bar back-squat peak ankle flexion

Reference	Athletes (*n*) and gender	Sport	Conditions	Load (%RM)	Angle (°)	Significance (p)
(Hales, Johnson, & Johnson, 2009)	25 M	Powerlifting	Begin of ascent	100% 1RM	55 ± 6	< 0.01
(Fry, Aro, Bauer, & Kraemer, 1993)	6 M	Olympic weightlifting and powerlifting	Segment angle	50% 1RM	56 ± 6	
(Swinton et al., 2012)	12 M	Powerlifting	Traditional squat	30, 50 & 70% 1RM	27 ± 5	< 0.05

M, Male. All angle data presented as mean ± standard deviation.

Table 6: High-bar back-squat peak ankle flexion

Reference	Athletes (*n*) and gender	Sport	Conditions	Load (%RM)	Angle (°)	Significance (p)
(Flanagan & Salem, 2007)	9 M & 9 F	Experienced recreational lifters	LHS	25% 1RM	27 ± 5	
			RHS	25% 1RM	27 ± 5	
			LHS	50% 1RM	26 ± 5	
			RHS	50% 1RM	26 ± 5	
			LHS	75% 1RM	25 ± 5	
			RHS	75% 1RM	25 ± 5	
			LHS	100% 1RM	24 ± 6	
			RHS	100% 1RM	24 ± 5	
(Sato, Fortenbaugh, & Hydock, 2012)	20 M & 5 F	Team sports	Weightlifting shoes	60% 1RM	39 ± 4	
			Running shoes	60% 1RM	35 ± 6	
(Kobayashi et al., 2010)	18 M	University long jump	Take off leg	50% 3RM	29 ± 6	
			Non-take off leg	50% 3RM	29 ± 6	
			Take off leg	70% 3RM	29 ± 5	
			Non-take off leg	70% 3RM	29 ± 5	
			Take off leg	90% 3RM	28 ± 4	
			Non-take off leg	90% 3RM	28 ± 5	
(Fry, Aro, Bauer, & Kraemer, 1993)	6 M	Olympic weightlifting and powerlifting	Segment angle	50% 1RM	53 ± 6	
(Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012)	12 M	Powerlifting	Traditional squat	30, 50 & 70% 1RM	37 ± 4	

M, Male; F, Female; RHS, Right hand side; LHS, Left hand side; 1RM, One repetition maximum; 3RM, Three repetition maximum. All angle data presented as mean ± standard deviation.

Findings: Kinetics

Ground reaction forces (GRF's) are based on the concept of Newton's third law of motion and are a combination of vertical and horizontal forces that act on the ground, through the movement and interaction from a person or object. The magnitude of these forces (N) can be measured by technology such as scales and force plates (Bobbert & Schamhardt, 1990; Kram, Griffin, Donelan, & Chang, 1998). Analysis of GRFs can aid in the calculation of joint moments of the knee and hip when paired with segment orientation (Faber, Kingma, & van Dieën, 2010). In the BBS, GRF location and load on the lower extremity is influenced largely by the position of the upper body, due its larger mass (Chiu, 2009). As the mass lifted is increased in a back-squat, the resultant GRF produced is increased significantly and proportionally to the size of load increase (Flanagan & Salem, 2007; Kellis, Arambatzi, & Papadopoulos, 2005; Zink, Perry, Robertson, Roach, & Signorile, 2006). An increase in GRF due to increased load is significant in both the concentric and eccentric phases of the BBS (Ebben & Jensen, 2002; Ebben et al., 2012). Furthermore, if the weight that is lifted in a back-squat, is placed un-evenly on the shoulders, the GRF observed will be relatively larger than if the same weight is evenly distributed across the shoulders (Sato & Heise, 2012). Likewise, as was shown in one study, if the load is unstable (suspended from the bar by elastic bands), the resulting peak vertical GRF F_v observed will present as significantly ($p < 0.05$; % Diff = 3.9) less than with a stable bar (Table 7) (Lawrence & Carlson, 2015). The loads and movement tempos were equal in both the stable and unstable conditions in this study, and therefore the decrease in force production can be attributed to the effect of the elastic bands in the unstable condition (Lawrence & Carlson, 2015).

The speed of a BBS may affect the F_v that is produced. Bentley, Amonette, De Witt, and Hagan (2010) showed that when lifting a mass that is equal to the participant's body weight with either a fast cadence (1 second descent, 1 second ascent), medium cadence (3 seconds descent, 1 second ascent), or a slow cadence (4 seconds descent, 2 second ascent), a fast cadence produced the largest peak F_v ($P = 0.0002$), and greatest ranges of F_v ($P = 0.05$). In contrast, Lake, Lauder, Smith, and Shorter (2012) showed no significant differences in the F_v produced between a ballistic jump-squat (fast cadence), and non-ballistic BBS (slow cadence). Both the ballistic and non-ballistic movements were performed at 45% of 1RM. The contrasting results from these two studies may have resulted from differences in load between exercises. The body weights of the participants in the first study equated to a larger load than the 45% of 1RM lifted in the second study. Therefore, there may not have been sufficient load applied to the ballistic jump-squat to produce a larger F_v than the non-ballistic

Table 7: High-bar and low-bar back squat kinetic results

Reference	Athletes (n) and gender	Sport	Conditions	Bar Load (kg/%RM)	Peak F_v (N)	Mean F_v (N)	Significance
(Kellis, Arambatzi, & Papadopoulos, 2005)	8 M	Experienced recreational lifters	Smith machine squats	10% 1RM	2.3 ± 0.2 *BW	1.7 ± 0.1 *BW	p < 0.05
				100% 1RM	3.2 ± 0.3 *BW	2.4 ± 0.2 *BW	p < 0.05
(Zink, Perry, Robertson, Roach, & Signorile, 2006)	12 M	Experienced recreational lifters	Standard parallel squats	20% 1RM	0.7 ± 0.1'		
				30% 1RM	0.7 ± 0.1'		
				40% 1RM	0.8 ± 0.1'		
				50% 1RM	0.8 ± 0.1'		
				60% 1RM	0.8 ± 0.0'		
				70 % 1RM	0.9 ± 0.0'		
				80% 1RM	0.9 ± 0.0'		
				90% 1RM	1.0 ± 0.0'		
(Ebben & Jensen, 2002)	6 F & 5 M	Volleyball (F), basketball (F), wrestling (M)	Traditional squat Ecc	100% 5RM	1401 ± 361	1188 ± 304	
			Traditional squat Con	100% 5RM	1603 ± 361	1260 ± 301	
			Chain squat Ecc	100% 5RM	1347 ± 367	1129 ± 334	
			Chain squat Con	100% 5RM	1528 ± 344	1238 ± 320	
			Elastic band squat Ecc	100% 5RM	1408 ± 357	1189 ± 318	
			Elastic band squat Con	100% 5RM	1603 ± 311	1229 ± 309	
(Ebben et al., 2012)	12 M	Experienced recreational lifters	Ecc	80% 1RM		2.8 ± 0.5 *BW	p ≤ 0.001
			Con	80% 1RM		3.2 ± 0.6 *BW	p ≤ 0.001
			Ecc	100% 1RM		3.3 ± 0.6 *BW	p ≤ 0.001
			Con	100% 1RM		3.7 ± 0.6 *BW	p ≤ 0.001
			Ecc	120% 1RM		3.6 ± 0.7 *BW	p ≤ 0.001
			Con	120% 1RM		4.1 ± 0.8 *BW	p ≤ 0.001
(Sato & Heise, 2012)	28 M/F	Intercollegiate athletics & mixed collegiate sports	Equal WtD group	60% 1RM		2.1 ± 1.6 *SI	
				75% 1RM		2.5 ± 1.8 *SI	
			Unequal WtD group	60% 1RM		4.4 ± 2.0 *SI	
				75% 1RM		4.9 ± 4.9 *SI	
(Lawrence & Carlson, 2015)	15 M	Experienced recreational lifters	Normal squat RHS	60% 1RM	1021 ± 175		p ≤ 0.05
			Normal squat LHS	60% 1RM	1039 ± 182		p ≤ 0.05
			Unstable squat RHS	60% 1RM	993 ± 164		
			Unstable squat LHS	60% 1RM	987 ± 155		
(Bentley, Amonette, De Witt, & Hagan, 2010)	6 M	Experienced recreational lifters	Fast cadence	BW	2.6 ± 0.1 *BW		p = 0.0002

			Medium cadence	BW	2.4 ± 0.1 *BW		$p = 0.0002$
			Slow cadence	BW	2.3 ± 0.1 *BW		$p = 0.0002$
(Lake, Lauder, Smith, & Shorter, 2012)	30 M	Experienced recreational lifters	Non-ballistic squat P	45% 1RM		1706 ± 251	
			Ballistic squat P	45% 1RM		1768 ± 261	
			Non-ballistic squat PB	45% 1RM		1324 ± 217	
			Ballistic squat PB	45% 1RM		1331 ± 207	
(Harman & Frykman, 1990)	9 M	Physically Active	Wraps	BW		254 ± 40	$p = 0.0005$
			No wraps	BW		365 ± 53	$p = 0.0005$
(Lake, Carden, & Shorter, 2012)	10 M	Experienced recreational lifters	Wrapped braking phase	80% 1RM	2447 ± 207	2221 ± 189	
			Wrapped propulsion phase	80% 1RM	2574 ± 300	2322 ± 213	
			Unwrapped braking phase	80% 1RM	2495 ± 262	2240 ± 198	
			Unwrapped propulsion phase	80% 1RM	2611 ± 378	2310 ± 256	
(Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012)	12 M	Powerlifting	Traditional squat	30% 1RM		2166 ± 194	
				50% 1 RM		2448 ± 295	$p < 0.05$
				70% 1RM		2680 ± 309	$p < 0.05$
			Powerlifting squat	30% 1RM		2165. ± 182	
				50% 1RM		2400 ± 270	$p < 0.05$
				70% 1RM		2685 ± 301	$p < 0.05$
			Box squat	30% 1RM		2080 ± 280	
				50% 1RM		2265 ± 306	$p < 0.05$
				70% 1RM		2528 ± 302	$p < 0.05$
(Goodin, 2015)	6 M	Experienced recreational lifters	High-bar	20% 1RM		2190 ± 54	$d > 0.80$
				30% 1RM		2402 ± 34	$d > 1.30$
				40% 1RM		2632 ± 32	$d > 1.30$
				50% 1RM		2867 ± 39	$d > 1.30$
				60% 1RM		2931 ± 29	$d > 1.30$
				70% 1RM		3048 ± 28	$d > 1.30$
				80% 1RM		3146 ± 30	$d > 1.30$
				90% 1RM		3176 ± 25	$d > 0.20$
			Low-bar	20% 1RM		2121 ± 71	$d > 0.80$
				30% 1RM		2332 ± 30	$d > 1.30$
				40% 1RM		2573 ± 34	$d > 1.30$
				50% 1RM		2720 ± 22	$d > 1.30$

60% 1RM	2776 ± 45	d > 1.30
70% 1RM	2968 ± 32	d > 1.30
80% 1RM	3084 ± 28	d > 1.30
90% 1RM	3192 ± 49	d > 0.20

M, Male; F, Female; 1RM, One repetition maximum; 5RM, Five repetition maximum; *BW, Normalised to body weight; ', Normalised to peak of movement; Con, Concentric phase; Ecc, Eccentric phase; ", Value of 3rd repetition reported; WtD, Weight distribution; *SI, Symmetry index percentage; RHS, Right hand side; LHS, Left hand side; P, Propulsive phase only; PB, Propulsive & braking phases. d > 0.20, small Cohen's-d effect; d > 0.80, large Cohen's-d effect; > 1.30, Very large Cohen's-d effect. All angle data presented as peak/mean ± standard deviation.

BBS. Moreover, the ballistic jump-squat involves a flight phase, in which no contact is made with the ground. In this phase there is no force applied through the force plate. It is possible that the ballistic jump-squat did produce greater force; however, the force produced during the flight phase could not be recorded.

The use of elastic knee wraps when squatting, has also been shown to provide direct mechanical assistance to the BBS (Harman & Frykman, 1990; Lake, Carden, & Shorter, 2012; Totten, 1990). This manifests as an increased F_v, and as such elastic knee wraps are banned from non-equipped powerlifting and Olympic weightlifting (although knee sleeves that supposedly provide less elastic assistance are allowed) (Totten, 1990).

In two of the five studies specifically comparing the HBBS with the LBBS, differences were recorded and reported in F_v. Swinton et al. (2012) reported that both the HBBS and LBBS produced similar F_v profiles across all loads (no significant differences). Additionally, as load increased, the F_v time curve become more bimodal, with a noticeable increase in the second F_v peak. A larger second peak is expected with an increase in load and represents the force produced overcoming the 'sticking' point or region (van den Tillaar, Andersen, & Saeterbakken, 2014). Goodin (2015) compared the HBBS to the LBBS with loads up to 90% of each participants HBBS 1RM. The HBBS produced larger peak force with loads of 20-80% 1RM, larger peak power with loads of 20-60% 1RM and 80-90% 1RM, greater total work with loads of 20%, 40%, and 60-90% 1RM, as well as greater peak velocity and vertical displacement at all loads. However, the LBBS produced greater impulse at 30-90% 1RM than the HBBS.

In addition to differences in squat depth, the HBBS and LBBS are typically characterised by different stance widths. Although there are no limits placed for the stance width of either BSS variation, the LBBS is typically performed with a stance wider than shoulder width (97% - 183%) (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001), and the HBBS is typically performed at shoulder width (Chandler & Stone, 1992). One study has analysed the F_v of a BBS at different stance widths. Swinton et al. (2012) showed that both a typical HBBS stance (shoulder width) and a wider powerlifting style stance produced a larger F_v when compared to a BBS performed to a box at the same load, without significant differences between the stances.

In summary, any measured differences in GRF between the HBBS and LBBS are likely from differences in load and/or the speed of the movement. The greater load lifted by the LBBS may be attributed to the mechanical advantage created, through joint angles and shortened moment arm. The results above show limited differences between the HBBS and LBBS in GRF, and may not portray these mechanical differences effectively. The analysis of joint angles or muscle activity may be more appropriate to determine if and why a LBBS allows heavier loads to be lifted. Further research should look to compare the HBBS to the LBBS across a full range of loads, to create a full profile and understanding of GRF differences between the two BBS variations.

Muscle Activity

The BBS is routinely included as a lower body training exercise. This is due to the contributions of the quadriceps, hamstrings, gluteal and triceps surae muscle groups to the completion of the movement (Escamilla, 2001; Robertson, Wilson, & Pierre, 2008). There is also a large contribution from the erector muscles in the lumbar region (Maddigan, Button, & Behm, 2014). In fact, it is predicted that in total, there are over 200 active muscles used in the completion of a BBS repetition (Nisell & Ekholm, 1986; Stoppani, 2006). Electromyography (EMG) is a method of assessing muscle function, through recording and analysing the electrical activity that muscle activation produces. There are two kinds of EMG: surface EMG (sEMG) and intramuscular EMG (iEMG). sEMG involves the application of electrodes to the skin's surface, whereas the iEMG utilises fine wires inserted directly into the muscle under the skin's surface (Raez, Hussain, & Mohd-Yasin, 2006). The most common variety of EMG used in researching the BBS is the sEMG, due to an increased number of potential muscle sites, as intramuscular EMG is used only for deep muscles (Raez, Hussain, & Mohd-Yasin, 2006). Several recent studies have shown sEMG to have a moderate to excellent reliability with an ICC range of 0.600 to 0.985 (Hashemi Oskouei, Paulin, & Carman, 2013; Katsavelis & Joseph Threlkeld, 2014; Mutchler, Weinhandl, Hoch, & Van Lunen, 2015; Olstad, Zinner, Cabri, & Kjendlie, 2014; Varghese, Hui-Chan, Wang, & Bhatt, 2014).

The majority of the EMG studies on the BBS have used the HBBS, with only two studies specifically analysing the activity of the LBBS (McCaw & Melrose, 1999; Wretenberg, Feng, & Arborelius, 1996). In addition, studies using the HBBS have assessed changes in muscular activity under different stability conditions (Anderson & Behm, 2005; Bressel, Willardson, Thompson, & Fontana, 2009; Ebben & Jensen, 2002; Fletcher & Bagley, 2014; Lawrence & Carlson, 2015; McBride, Cormie, & Deane, 2006; Willardson, Fontana, & Bressel, 2009). Others have then analysed the muscular activity of the HBBS in comparison to common therapeutic exercises (Andersen et al., 2006; Hamlyn, Behm, & Young, 2007; Nuzzo, McCaulley, Cormie, Cavill, & McBride, 2008), open kinetic chain exercises (Escamilla et al., 1998; Maddigan, Button, & Behm, 2014; Signorile et al., 1994; Wilk et al., 1996), the front-squat (Gullett, Tillman, Gutierrez, & Chow, 2009; Yavuz, Erdağ, Amca, & Aritan, 2015), and single-leg squats (DeForest, Cantrell, & Schilling, 2014; McCurdy et al., 2010). Furthermore, the HBBS has been used to demonstrate differences in muscular activity resulting from training status / experience (Panissa, Azevedo Neto, Julio, Pinto E Silva, & Franchini, 2013; Pick & Becque, 2000), training time-of-day (Sedliak, Finni, Peltonen, & Hakkinen, 2008), and to examine the existence of a 'sticking point' (van den Tillaar, Andersen, & Saeterbakken, 2014). These studies demonstrate, under a variety of different conditions, that the HBBS produces activity in major muscle groups of the lower limb and trunk. Therefore, because the HHBS requires the contribution of so many muscle groups, it is seen as a valuable training stimulus in strength and conditioning and sporting contexts to induce muscular adaptations.

The LBBS is characterised by a greater forward lean at the trunk in comparison to the HBBS (O'Shea, 1985). As forward lean increases, it has been shown that a resulting increase in lumbar erector spinae muscle activity occurs (Toutoungi, Lu, Leardini, Catani, & O'Connor, 2000). This increased activity ensures that the lower back is able to effectively receive load, without undue stress to the region. In addition, due to the wider stance width that is common for the LBBS (Chandler & Stone, 1992; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001) a different EMG profile arises from this squat variation. Escamilla et al. (2001) observed a significantly larger EMG amplitude in the gastrocnemius via a narrow stance squat in comparison to a wide stance. Furthermore, McCaw and Melrose (1999) compared the EMG differences in the rectus femoris, vastus medialis, vastus lateralis, adductor longus, biceps femoris, and gluteus maximus during the parallel LBBS at different stance widths and bar loads. They observed no change in quadriceps activity with a different stance width, but there was a higher EMG in the adductors and gluteus maximus with a wider stance. Anderson et al., (1998) observed similar outcomes as McCaw and Melrose (1999), finding no significant differences in the EMG of the vastus medialis and vastus lateralis with a change in stance width. However, Anderson et al., (1998) did not assess gluteus maximus activity. The resultant increase in gluteus maximus activity from a wider stance width was also shown by Paoli, Marcolin, and Petrone (2009), during the performance of the HBBS. The authors propose that the lack of change in quadriceps muscle activity during different stance widths, results from similar muscle lengths in both stances. On the other hand, longer muscle length may explain the increase in adductor and gluteus maximus activity as stance widens.

However, the higher EMG in the gluteus maximus with increased stance width was only observed with high loads, which draws into question whether an increase in muscle activity results from increases in load or changes in muscle length. Contrastingly, Wretenberg et al. (1996) found that the EMG of the vastus lateralis, rectus femoris and also the biceps femoris muscles were larger (as deemed by a 95% confidence interval) during the performance of the LBBS by six powerlifters who typically use a wider stance, when compared to the HBBS as performed by eight weightlifters. However, the only muscle to demonstrate a significant difference was the rectus femoris ($p < 0.05$). The EMG results of this study were normalised to a three second parallel squat hold, at 65%1RM for each participant. Therefore, the significant increase in rectus femoris muscle activity in LBBS, can be seen as a result of the technical differences between the HBBS and LBBS. The larger muscle activities (not significant) shown for all other muscles by the LBBS can be explained through the relationship of EMG and load; the heavier the load, the greater the expected muscle activity. The muscle activity results of this study are presented as a representation of the two groups of participants; the powerlifters (LBBS) and the Olympic weightlifters (HBBS). However, the powerlifters themselves were heavier as a group, and lifted greater loads than the Olympic weightlifters, and therefore would naturally be expected to present larger EMG amplitudes.

As described in the joint angles section of this review, the differences in squat depth between the HBBS and LBBS can influence the corresponding muscle activity. Wretenberg, Feng, Lindberg, and Arborelius (1993) showed that in the vastus lateralis, rectus femoris, and long head of biceps femoris, muscle activity generally increases with depth, from 45° to 90° and to 'parallel' where the posterior borders of the hamstrings muscles are parallel to the floor. However, Wretenberg et al. (1993) observed no further increase in muscle activity with a deep squat past parallel (knees maximally flexed). This may imply that for the specific purpose of training the quadriceps, parallel squats could be sufficient, without a benefit from performing deeper squats. Similar to Wretenberg et al. (1993), Gorsuch et al. (2013) showed that squatting to a knee angle of 90° increased the activation of the rectus femoris and lumbar erector spinae muscles more so than when squatting to a depth of 45°. Pereira et al. (2010) also showed that the muscular activity of the thigh was most active in the bottom 30° of BBS, in both the eccentric and concentric phases. However, Caterisano et al., (2002) demonstrated no change in muscle activity in the vastus medalis, vastus lateralis, or biceps femoris with increased squat depth, instead they observed EMG activity changes only in the gluteus maximus. The premise that performing squats past parallel only serves to increase the EMG activity in the gluteus maximus rather than the quadriceps is also supported in a review by Schoenfeld (2010). Gastrocnemius activity rises as the athlete increases their knee angle (knee flexion). Drawing on the present literature, it is difficult to conclude what differences exist in muscular activity of the lower limb between the HBBS and LBBS. However, the differences that do exist seem interrelated with the associated depths typically displayed in each squat variation. Further research is required to provide an authoritative text on the matter.

In powerlifting and Olympic weightlifting, it is common for athletes to employ a variety of external material aids such as weightlifting/squat shoes/boots (International Weightlifting Federation, 2015; Sato, Fortenbaugh, & Hydock, 2012; Sato, Fortenbaugh, Hydock, & Heise, 2013), thick belts (Aurslanian, 1993; Bourne & Reilly, 1991; Faigenbaum & Liatsos, 1994; Harman, Rosenstein, Frykman, & Nigro, 1989; Kingma et al., 1976; Lander, Hundley, & Simonton, 1992; Lander, Simonton, & Giacobbe, 1990; McGill, Norman, & Sharratt, 1990; Miyamoto, Iinuma, Maeda, Wada, & Shimizu, 1999; Renfro & Ebben, 2006; Zink, Whiting, Vincent, & McLaine, 2001), and elastic knee wraps (Harman & Frykman, 1990; Totten, 1990) that may influence muscular activity throughout a BBS. When performing a BBS in standard running shoes, Sinclair, McCarthy, Bentley, Hurst, and Atkins (2014) reported a significantly greater activation in the rectus femoris compared to a barefoot condition, and no significant difference in activity was reported when weightlifting shoes were worn. Prior research does not provide a general consensus for the level of muscle activity in the trunk and back extensor muscles when squatting with and without a belt (Bauer, Fry, & Carter, 1999; Kurustien, Mekhora, Jalayondeja, & Nanthavanij, 2014; Lander, Simonton, & Giacobbe, 1990; McGill, Norman, & Sharratt, 1990; Miyamoto, Iinuma, Maeda, Wada, & Shimizu, 1999; Warren, Appling, Oladehin, & Griffin, 2001; Zink, Whiting, Vincent, & McLaine, 2001). Elastic knee wraps however, have been shown to significantly increase ($p < 0.05$) the muscle activity of the vastus lateralis muscle and gluteus maximus activity at 65% 1RM and 90% 1RM respectively (Gomes et al., 2015). However, elastic knee wraps in particular, not knee sleeves (which supposedly provide elastic assistance) have been shown to provide direct mechanical assistance to lifters (Harman & Frykman, 1990; Lake, Carden, & Shorter, 2012; Totten, 1990), and as such are banned from non-equipped powerlifting and Olympic weightlifting (Totten, 1990).

In summary, prior research has demonstrated that in comparison to the HBBS the LBBS results in increased erector spinae muscle activity due to the increased forward lean, increased activity of the adductors and gluteal muscles, and reduced gastrocnemius activity from a wider stance width. There are also typically larger loads lifted in the LBBS, which results in a greater overall muscle activity. It can be proposed, that if the goal is to increase strength or muscle size in the posterior kinetic chain, the LBBS may be a preferable exercise rather than the HBBS. However, those looking to induce anterior kinetic chain, and quadriceps specific adaptations, may be advised to perform the HBBS.

Conclusion

The purpose of this review was to examine the specific literature relating to the HBBS and LBBS, with the hope of understanding if and why the LBBS allows for greater loads to be lifted. Based on this information, we concluded that the answer to this question may be found in the differences in joint angles; specifically, the greater forward lean and reduced knee flexion (reduced depth) in the LBBS, resulting in maximisation of the force producing ability from posterior displacement of the hip. There may also be a greater activation of major muscles groups such as the gluteal muscles throughout the LBBS when compared to the HBBS. Future research should develop further on this analysis. Moreover, the current kinetic and kinematic, and muscle activity differences between the HBBS and LBBS beyond 90% 1RM are unknown. Therefore, future research up to and including maximal effort should be performed.

CHAPTER THREE - The high-bar and low-bar back-squat: A kinematic and kinetic analysis

Preface

This chapter is an original investigation into the kinematic, and kinetic differences between the HBBS and LBBS up to and including maximal effort. Currently, no study has completed an analysis of the HBBS in comparison to the LBBS above 90% of 1RM. Thus, the purpose of this study is to fill this gap in the current literature, by providing a full kinematic and kinetic analysis between the HBBS and LBBS, to determine if and why the LBBS allows for greater loads to be lifted. A greater understanding of the mechanisms behind each squat style, will have practical applications for Olympic weightlifters, powerlifters, and general strength athletes alike.

Introduction

In current strength and conditioning practice, the BBS is commonly regarded as a fundamental movement for the assessment, and improvement of lower limb muscle strength, function, and resilience to injury (Comfort, Stewart, Bloom, & Clarkson, 2014; Cormie, McCaulley, & McBride, 2007; Cormie, McCaulley, Triplett, & McBride, 2007; Cormie, McGuigan, & Newton, 2010a, 2010b; Escamilla, 2001; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; McCaw & Melrose, 1999; Senter & Hame, 2006; Sleivert & Taingahue, 2004; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). The BBS is performed with a barbell placed posteriorly to the shoulders, across the trapezius musculature (Gullett, Tillman, Gutierrez, & Chow, 2009), and is extensively used as a training stimulus for a variety of sports, including strength and power sports such as Olympic weightlifting and powerlifting, as well as endurance and team sport (Dintiman & Ward, 2003; Gamble, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). This is due to the contributions of the quadriceps, hamstrings, gluteal and triceps surae muscle groups to the completion of the movement (Escamilla, 2001; Robertson, Wilson, & Pierre, 2008) and there is also a large contribution from the erector muscles in the lumbar region (Maddigan, Button, & Behm, 2014). In fact, it is predicted that in total, there are over 200 active muscles used in the completion of a BBS repetition (Nisell & Ekholm, 1986; Stoppani, 2006).

The movement is initiated by the simultaneous flexion of the lower extremity kinetic chain; the hip, knee and ankle joints (Palmitier, An, Scott, & Chao, 1991), in order to lower the hips to a desired distance from the ground, before ascending back to the original upright position (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). There are two different variations of the BBS, differentiated by the placement of the barbell on the trapezius musculature. The HBBS is performed with the barbell placed across the top of the trapezius, just below the process of the C7 vertebra. The HBBS is commonly used by Olympic weightlifters to simulate the catch position of the Olympic weightlifting competition lifts; the snatch and clean and jerk (Wretenberg, Feng, & Arborelius, 1996). The LBBS places the barbell on the lower trapezius, just over the posterior deltoid and along the spine of the scapula (Wretenberg, Feng, & Arborelius, 1996). In addition, the LBBS is also typically characterised by a wider stance width than the HBBS (Chandler & Stone, 1992; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001). The LBBS is commonly used in competitive powerlifting (where the BBS is one of the three competition lifts), as it may enable higher loads to be lifted (O'Shea, 1985). This could be due to the maximisation of posterior displacement of the hips, and increased force through the hip joints in comparison to the knee joints (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012).

Differences in bar position between the HBBS and LBBS result in an altered centre of mass (COM). Therefore, different movement strategies are employed to ensure that the COM remains in the base of support (BOS) for balance during the execution of these lifts. These movement strategies manifest as differences in; 1) joint angles of the lower extremity kinetic chain, 2) GRF produced and, 3) the EMG activity of key muscles. As previously mentioned, competitive powerlifters will typically perform the LBBS variation both in training and in competition due to the potential ability to lift greater loads (Schick et al., 2010).

There are competition regulations that each lifter must comply with in order for each lift to count towards their competition total in powerlifting competition (International Powerlifting Federation, 2015). One such regulation is that sufficient 'depth' must be reached in the squat. That is, there must be sufficient flexion of the knees and lowering of the hips towards the ground, so that "the top surface of the legs at the hip joint are lower than the top of the knees" (International Powerlifting Federation, 2015). In comparison, the HBBS is not directly included as a competition lift in Olympic weightlifting. Therefore, in training Olympic weightlifters typically squat to a depth that replicates the final catch position of the snatch and clean and jerk. This often manifests as a deeper squat position than powerlifting regulation depth, characterized by greater flexion at the hip, knee and ankle joints. Prior research has shown that the angle at peak knee flexion is generally smaller in the HBBS (e.g. 70-90°), in comparison to the LBBS (e.g. 100-120°) (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2001; Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Han, Ge, Liu, & Liu, 2013; Hooper et al., 2014; Kobayashi et al., 2010; McKean, Dunn, & Burkett, 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; van den Tillaar, Andersen, & Saeterbakken, 2014). Interestingly, some studies have reported the reverse (Hales, Johnson, & Johnson, 2009; Kobayashi et al., 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). These conflicting results (although not explicitly stated by the authors), are likely to be the raw joint angles and not the actual angle (Figure 2).

Moreover, prior research specifically comparing the HBBS to the LBBS shows that the LBBS is defined by a smaller absolute trunk angle, and therefore greater forward lean (Benz, 1989; Fry, Aro, Bauer, & Kraemer, 1993; Wretenberg, Feng, & Arborelius, 1996). This forward lean, is required to maintain the barbell over the COM, which effectively maximises the posterior displacement of the hips, and therefore increases the force placed on the hips, in comparison to the knee joints. The unique position of the LBBS results in 1) a decreased trunk lever arm when placing the bar lower on the back, 2) a greater emphasis on the stronger musculature of the hip rather than the musculature of the knee joint and, 3) an increase in stability and a potential decrease in stress placed on the lumbar region and ankle, when compared to the HBBS (Sato, Fortenbaugh, & Hydock, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). These factors may contribute to understanding why the LBBS typically allows for greater loads to be lifted. However, these kinematic findings are not definitive and there are mixed results in the literature for the size of HBBS and LBBS trunk angles at peak hip flexion (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2001; Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Hooper et al., 2014; Kobayashi et al., 2010; McKean, Dunn, & Burkett, 2010; McLaughlin, Dillman, & Lardner, 1977; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). Similarly, no conclusive differences between the HBBS and LBBS ankle joint angles can be drawn, in reference to prior literature (Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Kobayashi et al., 2010; Sato, Fortenbaugh, & Hydock, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012).

As the position of the barbell on the trapezius influences the joint angles of the BBS, there is also a resultant influence on the GRF produced. The position of the upper body (i.e. hip joint angle) has a large impact on the location and magnitude of the resultant vertical force (F_v) due to its larger mass (Chiu, 2009). Moreover, as the load that is applied to the trapezius musculature via the barbell is increased, the resultant F_v produced is increased significantly and in proportion to the load increase in both the concentric and eccentric phases of the squat movement (Ebben & Jensen, 2002; Ebben et al., 2012; Flanagan & Salem, 2007; Kellis, Arambatzi, & Papadopoulos, 2005; Zink, Perry, Robertson, Roach, & Signorile, 2006). Due to the LBBS tending to allow for greater loads to be lifted, it would be expected that the F_v produced with this would be greater than with the HBBS. However, two studies have specifically compared the GRF profiles of the HBBS and LBBS, and provide contradictory results to this expectation. Goodin (2015) compared the HBBS to the LBBS with loads up to 90% of each participants' HBBS 1 repetition maximum (RM). It was found that the HBBS produced larger peak F_v with loads of 20-80% 1RM, larger peak power with loads of 20-60% 1RM and 80-90% 1RM, greater total work with loads of 20%, 40%, and 60-90% 1RM, as well as greater peak velocity and vertical displacement at all loads. However, the LBBS was shown to produce greater impulse at 30-90% 1RM than the HBBS. These results may indicate that, although the LBBS typically allows for greater load to be lifted, though apparent mechanical advantages, such as a decreased trunk lever arm, these mechanical advantages do not transfer effectively into F_v. Furthermore, the results of these studies specifically may have arisen due to the level of expertise of the participant with performing the LBBS. Although each participant in this study was an experienced weight trainer, with a background in Olympic weightlifting and/or powerlifting, the authors chose to target the HBBS in recruitment, as the focus for expertise. Impulse is the magnitude of force applied, relative to the time over which it is applied ($I=F \cdot \Delta t$) (Enoka, 1988). Impulse is an integral factor in Olympic weightlifting where muscular force must be developed quickly (< 200ms) in order to complete each lift (Storey, Wong, Smith, & Marshall, 2012; Wilson, Lyttle, Ostrowski, & Murphy, 1995). Similarly, the rate of force development is a characteristic of net impulse and a measure of acceleration. That is, the change in force over a given time frame, divided by the time (e.g. 0-50ms) ($RFD=\Delta F/t$) (Sands, McNeal, & Shultz, 1999). The greater impulse in all loads tested by Goodin (2015) indicates that the LBBS applied greater levels of F_v across the duration of the movement, in comparison to the HBBS. A greater F_v across the duration of the movement, is an indicator of increased ability to lift larger loads. The second study to specifically compare the GRF profiles of the HBBS and LBBS compared the HBBS to the LBBS performed at 30, 50 and 70% of 12 powerlifters LBBS 1RM, and reported that both the HBBS and LBBS produced similar vertical GRF profiles across all loads (no significant differences) (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). Therefore, further research is warranted to understand the GRF differences between the HBBS and LBBS, in particular with loads greater than 90% 1RM.

The existing literature provides some insight into the kinematic and kinetic differences between the HBBS and LBBS. However, there is no consensus as to the differences between the two BBS variations. At present, no prior study has compared the joint angles and GRFs of the HBBS and LBBS above 90% 1RM. Thus, the purpose of this study was to compare and contrast the differences in joint angles and GRFs of the HBBS and LBBS, up to and including maximal effort, in an effort to create a full profile of the two BBS variations. The results of this investigation will add to the current body of knowledge of Olympic weightlifting and powerlifting practice alike, as well as providing an understanding of why the LBBS allows for greater load to be lifted.

Methods

Experimental approach to the problem

A cross-sectional design was used to quantify the kinematic joint angles and kinetic GRF differences between the LBBS in powerlifters and the HBBS in Olympic weightlifters during a squat session which included warm up sets leading up to and including 100% of 1RM. Recreationally trained athletes served as a control group and performed both the HBBS and LBBS.

An a priori statistical power analysis (two-tailed, independent t-test) using the knee flexion angles at the start of the concentric phase reported by Swinton, Lloyd, Keogh, Agouris, and Stewart (2012) and G*Power software determined a total sample size of 12 participants; 6 Olympic weightlifters and 6 powerlifters will be required for this research (effect size d = 2.32, α err prob = 0.05, Power (1 –β err prob. = 0.95, and Allocation ratio N2/N1 = 1).

Participants

Six male powerlifters (height: 179.2 ± 7.8 cm; bodyweight: 87.1 ± 8.0 kg; age: 27.3 ± 4.2 years) of international (i.e. Oceania championships) level volunteered to participate in the LBBS group. In addition, six male Olympic weightlifters (height: 176.7 ± 7.7 cm; bodyweight: 83.1 ± 13 kg; age: 25.3 ± 3.1 years) who had previously qualified for national championship level competition volunteered to participate in the HBBS group. All powerlifters routinely performed the LBBS in training and competition, and all Olympic weightlifters routinely performed the HBBS in training. Finally, six recreationally trained male athletes (height: 181.9 ± 8.7 cm; bodyweight: 87.9 ± 15.3 kg; age: 27.7 ± 3.8 years) volunteered as a control group and each participant was required to perform both the LBBS and HBBS in a randomised order, after two familiarisation sessions with both types of squat. All participants were free of injury and had ≥ 1 year's strength training experience (powerlifters: 5.05 ± 4.56 years; Olympic weightlifters: 3.75 ± 2.72 years; recreational: 8.67 ± 3.5 years) consisting of ≥ 3 training sessions per week for the powerlifters and Olympic weightlifters. The control group volunteers were required to train the back-squat in ≥ 1 training sessions per week. Prior to testing, written informed consent was received from each participant and all testing conditions were examined and approved by the Auckland University of Technology Ethics Committee (14/398).

Testing sessions

Powerlifters and Olympic weightlifters

The powerlifters (POW) and Olympic weightlifters (OLY) were required to attend only one session of approximately three hours in duration. A full level two anthropometric assessment was performed on all athletes by an experienced International Society for the Advancement of Kinanthropometry (ISAK) anthropometrist followed by a LBBS 1RM test for the POW, and a HBBS 1RM test for the OLY.

Control group

The recreationally trained athletes (CON) were required to attend three separate sessions over the course of one week: two one-hour familiarisation sessions and one three-hour long testing session. An additional self-led familiarisation session was included prior to the maximal testing session of both squat variations (Figure 4). The first familiarisation session comprised of the 1RM testing protocol for HBBS and LBBS with loads up to 60% of self-reported or predicted 1RM. Self-reported 1RM values (performed within the last six months) for either back-squat variation were used to estimate load progressions. Pilot testing determined that the load of the unknown back-squat variation would be around 90% of the known back-squat 1RM regardless of which squat style was routinely performed. Thus, the loads for the familiarisation session were estimated from one known 1RM for one back-squat variation and a predicted 1RM at 90% of the known 1RM. The second familiarisation session was performed two days later and comprised the same HBBS and LBBS protocol in the same order as the first familiarisation session, up to 80% 1RM of the self-reported and predicted 1RM for either back-squat variation.

Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
Familiarisation session 1	X	X	Familiarisation session 2	X	'Self-directed' familiarisation session 3	X	Testing session

Figure 4: Representation of the order of familiarisation and testing dates for the control group.

In both the first and second familiarisation sessions for each participant, the resistance exercise-specific rating of perceived exertion (RPE) scale (Zourdos et al., 2015) (appendix 7) was used to ensure that intensity and predicted attempt weight values were correct. In the first familiarisation session, an RPE value of 3 or less (i.e. "light to little effort") was expected to be reported in line with the percentages of the 1RM (50, and 60%). If this was not achieved, the predicted weight values were changed for the second familiarisation session. In the second familiarisation session, the same RPE values of 3 or less were employed for the 50%, and 60% of predicted 1RM sets. After that, a self-reported RPE of 5 or less (i.e. "light effort with at-least 6 more repetitions possible") was expected for the 70%, and 80% of 1RM sets. If these RPE values were not achieved, the predicted 1RMs for both back-squat variations were changed for the final testing session. In the period between the second familiarisation session and final testing session, a self-directed familiarisation session was included for each participant to re-inforce the skills learned in the previous familiarisation sessions, and to provide a chance to practice each bar position prior to the testing. Each participant was asked not to exceed an RPE of 5 in this session, and to do no more than three sets. The final testing session was performed three days later and comprised of a full anthropometric assessment, followed by a 1RM test of both the HBBS and LBBS in random order so that half of the control group performed the HBBS first, and the other half performed the LBBS first. This randomised order was employed to minimise any fatigue affect from performing two maximal squat tests in one testing session.

Back-squat 1 RM test procedures

All squats were completed in line with the International Powerlifting Federation's competition rules (International Powerlifting Federation, 2015). Both the HBBS and LBBS were deemed to be successful lifts if the athlete was able to safely lower the bar to a minimum accepted depth (the top surface of the legs at the hip joint are lower than the top of the knees) or lower, through a bending of the knees, and then recover at will to a stance with knees locked, without the aid of any spotters. The OLY participants were instructed to squat to the usual depth they perform in training. Specific focus was placed on ensuring correct depth was obtained, the legs were completely locked out at the conclusion of each repetition, and no downward movement was observed on the ascent.

Prior to testing, each participants beltless 1RM was estimated. If in normal training, the participant did not use a weight belt, the athlete's predicted beltless 1RM was used. If the participant used a weight belt in normal training, and had a known belted 1RM, this belted 1RM was used to predict the athletes beltless 1RM. Pilot testing determined that the beltless 1RM is approximately 90% of a belted 1RM. Weightlifting shoes (comprised of a hard sole and slightly raised heel) were required to be worn by all participants and the heel height was required to be within the range of 1.5-2.0 centimetres. No other supportive aids beyond the use of wrist wraps were allowed to be worn during the test. Before all testing procedures, each participant completed a standardized dynamic warm consisting of: 1) 10 leg swings front and back, 2) 10 trunk twists, 3) 10 body weight squats, 4) 10 press-ups, 5) 10 wrist rotations clockwise, and 10 rotations anti-clockwise, 6) 5 'T' shoulder movements, and 7) 5 'Y' shoulder movements (Appendix 6).

The 1RM testing protocol was adapted from Matuszak, Fry, Weiss, Ireland, and McKnight (2003), and consisted of the participants performing 8 repetitions at 50% of the predicted 1RM, 3 repetitions at 60%, 2 repetitions at 70%, and 1 repetition at 80, and 90%. Additional warm up sets, prior to the initial 8 repetition set with 50% 1RM, were permitted with < 50% 1RM load if the participant desired to do so as to better replicate their normal warm up procedures. After the 90% of predicted 1RM lift, the participant was consulted as to what weight they would like to attempt for a maximal 1RM lift. An experienced strength coach along with the use of a Gymaware Powertool (Kinetic Performance Technology, Canberra, Australia) to measure the mean concentric velocity of the movement, assisted athletes in attempt selection to get as close to a true beltless 1RM as possible. Prior research has shown that maximal squat attempts performed by experienced lifters are typically performed at approximately 0.2 $m{\cdot}s^{-1}$ (0.24 ± 0.04 $m{\cdot}s^{-1}$) (Zourdos et al., 2015). Commonly a lift at 95% 1RM was performed prior to attempting the predicted maximal 1RM. After each successful attempt, small weight increments (1-5 kg) were made in order to obtain a true maximum. Between 3 and 5 minutes' rest was allowed between sets before the next weight was attempted.

Biomechanical instrumentation

Two embedded force platforms (Model AM6501, Bertec Corp., Columbus, Ohio, USA), were used to collect all kinetic squat data at a sampling rate of 1000Hz. The kinetic variables of interest included mean bar velocity ($m{\cdot}s^{-1}$); peak F_v ($N{\cdot}kg^{-1}$); impulse ($N{\cdot}kg^{-1}{\cdot}s$); RFD (0-50ms) ($N{\cdot}s^{-1}$); RFD (0-100ms) ($N{\cdot}s^{-1}$); RFD (0-200ms) ($N{\cdot}s^{-1}$); RFD (0-300ms) ($N{\cdot}s^{-1}$); RFD (0-400ms) ($N{\cdot}s^{-1}$), for both the eccentric and concentric phases. Mean bar velocity was chosen over peak bar velocity for a better representation of each athlete's ability to move load throughout the whole lifting phase (concentric/eccentric) (Jidovtseff, Harris, Crielaard, & Cronin, 2011). RFD is the change in force over a given time (Sands, McNeal, & Shultz, 1999), and the eccentric phase of each movement is where the body lowers and slows to a point of zero velocity, immediately prior to the start of the concentric ascent. The eccentric RFD is measured in the time before this change from the eccentric phase to the concentric phase. The two force platforms were arranged next to each other in the middle of the collection space to increase the chances of obtaining complete foot contact from each foot during the required movements. Kinematics were collected by nine infra-red cameras (T10S, Vicon Motion System Ltd., Oxford, UK) strategically placed around the force platforms in the collection space. The cameras were arranged so that each marker was always visible to a minimum of three cameras to allow for reconstruction of three-dimensional trajectories. The collection space was calibrated with an error of no greater than 0.2 (route mean squared in camera pixels; the difference between the 2D image of each marker on the camera sensor and the 3D reconstructions of those markers projected back to the cameras sensor) for each camera prior to each data collection session and a point of origin was positioned at the corner of one of the force platforms to establish a local relationship between the camera positions and the laboratory origin. Data from eight reflective markers (10mm diameter) placed in specific locations were used to analyse bar path and joint angles throughout the squat movement using Vicon Nexus software (Version 1.8.5, Vicon Motion System Ltd., Oxford, UK). Markers were placed in the centre of both ends of the barbell and on the right side of the athletes' bodies in specific anatomical locations following previous research (McKenzie, Brughelli, Whatman, & Brown, 2015). The markers were placed on the following locations: acromion process, greater trochanter, lateral epicondyle of the femur, lateral malleolus, top of the heal lift of the lifting shoe and in-line with the lateral malleolus and base of the fifth metatarsal to create five rigid segments.

Data reduction

Subsequent to the testing sessions, the two force platforms were combined and all data were filtered with a low-pass fourth-order zero-lag Butterworth filter using a cut-off frequency of 16 Hz in a custom-made LabVIEW programme (Version 14.0, National Instruments Corp., Austin, TX, USA) based on residual analysis and visual inspection of the kinematic and kinetic data. Kinematic variables of interest were gathered through an individual analysis within the start and finish of the squat to calculate the range-of-motion (peak flexion – initial or finishing flexion) and peak flexion angles for the hip, knee and ankle joints. Peak joint flexion was recorded as the angle at the lowest point of the lift, and peak extension at the highest point of the lift. The hip range-of-motion in the sagittal plane was derived from the anterior angle between the thorax (trunk) and the thigh, the knee range-of-motion was derived from the posterior angle between the thigh and the shank and the ankle range-of-motion was derived from the angle between the shank and the foot. In all cases, the actual angle is presented as opposed to the raw angle (see Figure 2). To obtain kinetic variables of interest, all repetitions were individually analysed during the eccentric phase (from the initiation of a negative [downward] velocity of the right-side bar marker to the instant the marker reached zero velocity [full depth]), and concentric phase (from the initiation of a positive [upward] velocity of the right-side bar marker to the instant the marker reached zero velocity a second time [the top]). Phase-linked kinetic data were then processed using the following equations:

Table 8: Kinetic variables and associated equations used in custom LabVIEW programme

Variable	Unit	Equation
Mean velocity ($\bar{v}$)	m·s^{-1}	$\bar{v} = \frac{s}{\Delta t}$
Peak relative force (F_v)	N·kg^{-1}	$F_v = ma$
Relative impulse (J)	N·kg^{-1}·s	$J = \int_{t1}^{t2} F\Delta t$
Rate of force development (RFD)	N·s^{-1}	$RFD = \frac{\Delta F}{\Delta t}$

Abbreviations: $\bar{v}$, velocity; F_v, vertical force; J, impulse; RFD, rate of force development; m, metre; s, second; N, Newton; kg, kilogram; s, displacement; Δ, derivative; t, time; m, mass; a, acceleration; $\int$, integral.

To obtain kinematic variables of interest, all repetitions were individually analysed within the start and finish of the squat movement to calculate the range-of-motion (peak flexion – initial flexion) and peak flexion angles for the hip, knee and ankle joints. From the sagittal plane, the hip range-of-motion was derived from the anterior angle between the thorax (trunk) and the thigh, the knee range-of-motion was derived from the posterior angle between the thigh and the shank and the ankle range-of-motion was derived from the angle between the shank and the foot. In all cases, the actual angle is presented as opposed to, the raw (Figure 2).

Statistical analysis

Prior to analyses, data were split into four categories according to the %1RM load: (1) 74-83%, (2) 84-93%, (3) 94-99%, and (4) 100%. Generalised linear mixed models using a normal distribution with an identity link and unstructured covariance structure were used to estimate the difference in outcome variables between bar height and subject group across all four load groups while adjusting for the random effect of subject. Modelling of individual subject variance allows the accommodation of missing values. Robust standard errors, constructed using the 'sandwich estimator' of the covariance structure, were used to control for possible misspecifications of the correlation structure. An alpha of 0.05 was used to determine significant associations. Multiple pairwise comparisons were corrected for inflation of Type 1 error using the Bonferroni method. Cohen's d statistic was calculated to provide additional information on the magnitude of the associations, with 0.2, 0.5, and 0.8 representing small, moderate, and large effects, respectively (Cohen, 1992). The analysis used IBM SPSS Statistics v. 23.0.0.0, IBM, Armonk, NY, USA) software.

Results

Initially, a comparison of the HBBS performed by the OLY and control group (HBCON), and the LBBS performed by the POW and CON group (LBCON) was completed to determine if the control group data could be combined with the OLY and/or the POW for the high and low bar positions, respectively. Significant joint angle differences ($p < 0.05$) were observed in knee flexion, and ankle range of motion (ROM) at 100% of 1RM for HBBS (OLY vs. HBCON), and in hip ROM at 84-93% 1RM and knee ROM at 100% 1RM for the LBBS (POW vs. LBCON). Significant differences for several kinetic variables across all four percentage ranges of 1RM for both HBBS (OLY vs. HBCON) and LBBS (POW vs. LBBS) were also observed. Therefore, in the following sections, the data has been analysed with all four groups displayed independently.

Load

The mean loads are presented in Tables 9 and 10. No significant differences were observed between OLY and POW, and HBCON and LBCON. However, on average the POW group lifted greater loads compared to the OLY group across all ranges of load ($d = 0.3$, 0.2, 0.2 and 0.2 for ranges of 74-83%, 84-93%, 94-99%, and 100% 1RM respectively). Small effect sizes indicated that greater loads and loads relative to body weight were lifted by the LBCON than the HBCON group for the 74-83% ($d = 0.3$ and 0.3, respectively), and 84-93% ($d = 0.3$ and 0.4, respectively) 1RM ranges, but only for load at 100% 1RM ($d = 0.4$). Moderate effect sizers indicated that greater loads were lifted by the LBCON in comparison to the HBCON group at 94-99% 1RM in both load and load relative to body weight ($d = 0.5$ and 0.6, respectively), and at 100% 1RM in load relative to body weight ($d = 0.5$).

Table 9: Mean loads lifted across all %1RM ranges

% Range	Variable	OLY	POW	HBCON	LBCON	OLY vs POW Diff; ±90%CI	HBCON vs LBCON Diff; ±90%CI
	BW (kg)	83.2 ± 13.0	87.1 ± 8.0	87.9 ± 15.3	87.9 ± 15.3		
74-83%	Load (kg)	136.6 ± 23.5	140.9 ± 20.1	99.9 ± 13.2	103.0 ± 16.2	12.5 ± 23.8	4.0 ± 7.6
	*BW	1.6 ± 0.2	1.6 ± 0.3	1.2 ± 0.2	1.2 ± 0.2	0.1 ± 0.3	0.1 ± 0.1
84-93%	Load (kg)	152.5 ± 23.1	159.2 ± 21.8	116.4 ± 12.9	121.7 ± 18.8	9.4 ± 26.6	6.0 ± 9.5
	*BW	1.8 ± 0.2	1.9 ± 0.4	1.3 ± 0.2	1.4 ± 0.2	0.0 ± 0.3	0.1 ± 0.1
94-99%	Load (kg)	164.0 ± 24.7	174.6 ± 20.1	128.7 ± 12.4	136.5 ± 21.6	7.2 ± 24.2	7.9 ± 8.0
	*BW	2.0 ± 0.2	2.0 ± 0.4	1.5 ± 0.2	1.6 ± 0.2	0.0 ± 0.3	0.1 ± 0.1
100%	Load (kg)	169.5 ± 26.5	181.2 ± 21.8	135.2 ± 11.1	143.4 ± 20.7	11.8 ± 25.4	8.2 ± 11.1
	*BW	1.9 ± 0.3	2.1 ± 0.4	1.6 ± 0.2	1.6 ± 0.2	0.1 ± 0.3	0.1 ± 0.1

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back squat; LBCON, Control low-bar back-squat; BW, Body weight; 1RM, One repetition maximum; CI, Confidence interval.
All data presented as mean ± standard deviation.

Table 10: Mean loads lifted effect sizes and percentage differences

		OLY vs POW		HBCON vs LBCON	
% Range	Variable	Effect Size	% Difference	Effect Size	% Difference
74-83%	Load (kg)	0.3*	3.2	0.3*	3.0
	*BW	0.1	0.2	0.3*	2.5
84-93%	Load (kg)	0.2*	4.4	0.3*	4.4
	*BW	0.0	0.8	0.4*	3.9
94-99%	Load (kg)	0.2*	6.5	0.5§	5.7
	*BW	0.0	2.5	0.6§	5.1
100%	Load (kg)	0.2*	6.9	0.4*	5.7
	*BW	0.1	3.0	0.5§	5.2

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back squat; LBCON, Control low-bar back-squat; BW, Body weight.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5.

Centre of pressure

The mean distances of the bar from the centre of pressure (COP) are presented in Table 11. In the experienced OLY and POW groups, there is a distinct difference between the two bar positions. The LBBS performed by the POW shows a greater average distance from the bar to the COP. In the less experienced CON group, the same difference is generally observed between the HBBS and LBBS, but is much less pronounced.

Kinematics

Differences in kinematics are presented in Tables 12 and 13. No significant differences were observed between the OLY and POW groups, in any condition. A significantly larger knee flexion angle was observed in the HBCON when compared to the OLY group ($p < 0.05$; d = 0.7; % Diff = 14.3) at 100% 1RM. Conversely, the OLY group displayed a significantly larger ankle ROM than the HBCON group at 100% ($p < 0.05$; d = 0.07; % Diff = 18.3). The only significant difference between the POW and LBCON groups was observed at 100% 1RM, with the POW group demonstrating a significantly larger knee ROM ($p < 0.05$; d = 0.8; % Diff = 18.9). The majority of significant results were observed between the HBCON and LBCON. Significant differences were observed in knee ROM at 74-83% 1RM, peak hip flexion at 84-93% 1RM, peak hip flexion at 94-99% 1RM and peak hip flexion, peak knee flexion, and knee ROM at 100% 1RM. In all cases the HBCON group displayed larger angles, except for peak knee flexion at 100% 1RM where the LBCON was greater.

Kinetics

Kinetic differences are presented in Tables 14 – 21. No significant differences in kinetic variables were observed between the OLY and POW groups in either the eccentric or concentric phases across all percentage ranges of 1RM. Small effects were observed for a variety of variables across all four ranges of load (%1RM). Moderate kinetic effects showing a greater OLY RFD were also observed in the eccentric phase of the squat at 74-83% 1RM 0-50ms (d = 0.6), and 0-100ms (d = 0.6), and at 84-93% 1RM at 0-200ms (d = 0.5), 0-300ms (d = 0.5), 0-400ms (d = 0.5). Moderately larger effects were also observed in the concentric phase in the OLY at 84-93% 1RM at 0-50ms (d = 0.6), and 0-400ms (d = 0.6), and at 94-99% 1RM (0-50ms) (d = 0.6). Only one significant difference between the HBCON and LBCON was observed. The HBCON group produced a significantly greater peak F_v in the eccentric phase at 94-99% 1RM ($p < 0.05$; d = 0.9; % Diff = 2.4), refer to Tables 18 and 19. A large number of significant differences ($p < 0.05$) were observed across all load ranges, in both the eccentric and concentric phases for OLY vs HBCON, and POW vs LBCON

Table 11: Distance of centre of pressure to bar results

% Range	OLY (mm)	POW (mm)	HBCON (mm)	LBCON (mm)
74-83%	-19 ± 42	-44 ± 31	-60 ± 45	-57 ± 18
84-93%	-20 ± 40	-58 ± 39	-51 ± 42	-72 ± 25
94-99%	-23 ± 29	-46 ± 31	-58 ± 35	-59 ± 38
100%	-24 ± 40	-74 ± 52	-39 ± 49	-51 ± 18

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back squat; LBCON, Control low-bar back-squat. Negative number represents the bar a distance behind the centre of pressure. All centre of pressure data is presented as mean ± standard deviation.

Table 12: Kinematic results

%1RM Range	Joint	Variable	High-Bar Back-Squat OLY Angle (°)	HBCON Angle (°)	OLY vs HBCON Diff; ±90%CI	OLY vs POW Diff; ±90%CI	Low-bar Back-Squat POW Angle (°)	LBCON Angle (°)	POW vs LBCON Diff; ±90%CI	HBCON vs LBCON Diff; ±90%CI
74-83%	Hip	Peak Flexion	69 ± 7	64 ± 5	6 ± 7	8 ± 10	59 ± 9	61 ± 4	3 ± 8	3 ± 3
		ROM	100 ± 8	105 ± 9	5 ± 10	6 ± 11	109 ± 11	101 ± 9	9 ± 12	4 ± 4
	Knee	Peak Flexion	54 ± 7	59 ± 8	3 ± 9	9 ± 11	62 ± 11	63 ± 8	1 ± 11	4 ± 4
		ROM	116 ± 7	110 ± 11^	3 ± 11	5 ± 12	114 ± 12	104 ± 10^	8 ± 13	5 ± 5
	Ankle	Peak Dorsiflexion	90 ± 5	88 ± 6	4 ± 6	2 ± 5	90 ± 5	90 ± 8	0 ± 7	2 ± 4
		ROM	33 ± 4	32 ± 3	0 ± 4	1 ± 6	33 ± 6	30 ± 4	2 ± 6	2 ± 3
84-93%	Hip	Peak Flexion	69 ± 9	64 ± 6^	6 ± 8	6 ± 11	59 ± 8	61 ± 3^	3 ± 7	3 ± 3
		ROM	100 ± 9	105 ± 10	6 ± 11	8 ± 11	111 ± 11	99 ± 9	13 ± 11	5 ± 5
	Knee	Peak Flexion	56 ± 7	61 ± 8	4 ± 8	7 ± 11	63 ± 12	67 ± 5	4 ± 10	6 ± 6
		ROM	114 ± 7	107 ± 11	5 ± 10	1 ± 12	113 ± 13	101 ± 6	12 ± 12	6 ± 6
	Ankle	Peak Dorsiflexion	91 ± 4	90 ± 6	2 ± 5	2 ± 5	90 ± 5	91 ± 7	1 ± 7	1 ± 3
		ROM	33 ± 4	30 ± 5	2 ± 4	2 ± 6	34 ± 7	30 ± 4	4 ± 6	0 ± 2
94-99%	Hip	Peak Flexion	71 ± 10	69 ± 6^	4 ± 9	12 ± 12	59 ± 9	61 ± 5^	2 ± 9	8 ± 8
		ROM	98 ± 10	100 ± 10	4 ± 11	11 ± 13	110 ± 14	100 ± 10	9 ± 14	0 ± 3
	Knee	Peak Flexion	56 ± 7	65 ± 8	8 ± 9	4 ± 10	62 ± 12	68 ± 5	5 ± 10	3 ± 4
		ROM	113 ± 8	103 ± 12	8 ± 12	2 ± 12	114 ± 13	101 ± 7	11 ± 12	6 ± 6
	Ankle	Peak Dorsiflexion	90 ± 5	91 ± 6	1 ± 6	0 ± 6	90 ± 5	92 ± 7	2 ± 7	1 ± 2
		ROM	33 ± 4	28 ± 4	4 ± 5	1 ± 6	33 ± 7	29 ± 3	4 ± 6	1 ± 2
100%	Hip	Peak Flexion	71 ± 9	68 ± 6^	3 ± 8	12 ± 12	59 ± 10	63 ± 6^	4 ± 8	5 ± 5
		ROM	97 ± 10	101 ± 10	4 ± 10	11 ± 12	109 ± 13	96 ± 11	13 ± 13	5 ± 5
	Knee	Peak Flexion	56 ± 7*	65 ± 6*^	9 ± 9	7 ± 11	63 ± 12	73 ± 6^	10 ± 10	7 ± 7
		ROM	113 ± 9	103 ± 9^	10 ± 10	0 ± 12	113 ± 14§	95 ± 8§^	18 ± 18	8 ± 8
	Ankle	Peak Dorsiflexion	90 ± 5	92 ± 6	1 ± 6	0 ± 6	91 ± 6	93 ± 6	3 ± 7	2 ± 2
		ROM	32 ± 3*	27 ± 4*	5 ± 5	1 ± 6	33 ± 8	27 ± 4	6 ± 6	0 ± 4

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; ROM, Range of motion; CI, Confidence interval.
All angle data presented at mean ± standard deviation.
* $p < 0.05$ OLY vs HBCON; § $p < 0.05$ POW vs LBCON; ^ $p < 0.05$ HBCON vs LBCON.

Table 13: Kinematic effect sizes and percentage differences

			OLY vs HBCON		POW vs LBCON		OLY vs POW		HBCON vs LBCON	
% Range	Joint	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
74-83%	Hip	Peak Flexion	0.5§	4.3	0.2*	2.7	0.4*	16.4	0.7§	5.1
		ROM	0.3*	7.4	0.4*	8.3	0.3*	8.0	0.6§	3.9
	Knee	Peak Flexion	0.2*	5.1	0.0	1.8	0.4*	12.0	0.6§	7.1
		ROM	0.2*	2.5	0.3*	8.8	0.2*	1.9	0.7§	5.2
	Ankle	Peak Dorsiflexion	0.3*	1.9	0.0	0.6	0.2*	0.7	0.3*	2.3
		ROM	0.1	15.9	0.2*	10.1	0.1	1.7	0.3*	5.9
84-93%	Hip	Peak Flexion	0.4*	7.9	0.2*	3.1	0.3*	16.2	0.8^	4.2
		ROM	0.3*	5.3	0.1	11.9	0.4*	10.2	0.6§	5.7
	Knee	Peak Flexion	0.3*	8.7	0.2*	6.4	0.3*	11.0	0.6§	9.5
		ROM	0.2*	6.2	0.6§	12.4	0.1	0.8	0.6§	6.2
	Ankle	Peak Dorsiflexion	0.2*	0.8	0.0	0.8	0.2*	0.4	0.2*	1.2
		ROM	0.2*	10.2	0.3*	14.6	0.2*	2.4	0.0	1.5
94-99%	Hip	Peak Flexion	0.2*	2.4	0.1	2.9	0.6§	19.5	2.3^	11.8
		ROM	0.2*	2.3	0.4*	9.4	0.4*	10.9	0.1	0.2
	Knee	Peak Flexion	0.4*	13.7	0.2*	7.9	0.2*	9.9	0.3*	4.0
		ROM	0.4*	10.0	0.5§	12.4	0.1	0.6	0.6§	1.6
	Ankle	Peak Dorsiflexion	0.1	1.0	0.1	1.9	0.0	0.1	0.2*	0.9
		ROM	0.4*	15.4	0.3*	13.9	0.1	1.9	0.2*	3.2
100%	Hip	Peak Flexion	0.2*	3.8	0.3*	6.6	0.7§	20.7	1.3^	7.9
		ROM	0.2*	3.6	0.5§	13.2	0.5§	10.5	0.6§	4.9
	Knee	Peak Flexion	0.7§	14.3	0.5§	13.7	0.3*	10.4	0.9^	10.9
		ROM	0.6§	9.9	0.8^	18.9	0.0	0.1	0.8^	7.7
	Ankle	Peak Dorsiflexion	0.1	1.3	0.2*	2.9	0.0	0.2	0.6§	1.9
		ROM	0.7§	18.3	0.5§	22.0	0.1	1.9	0.0	1.1

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; ROM, Range of motion.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 14: Kinetic results 74–83% 1RM

		High-Bar Back-Squat				Low-Bar Back-Squat			
Phase	Variable	OLY	HBCON	OLY vs HBCON Diff; ±90%CI	OLY vs POW Diff; ±90%CI	POW	LBCON	POW vs LBCON Diff; ±90%CI	HBCON vs LBCON Diff; ±90%CI
Ecc	Mean Bar v ($m.s^{-1}$)	0.51 ± 0.13	0.44 ± 0.11	0.09 ± 0.19	0.05 ± 0.10	0.54 ± 0.12§	0.38 ± 0.09§	0.20 ± 0.20	0.06 ± 0.07
	Peak F_v ($N.kg^{-1}$)	38 ± 3*	26 ± 4*	10 ± 10	1 ± 3	37 ± 2.69§	26 ± 3§	9 ± 9	1 ± 2
	Impulse ($N.kg^{-1}.s$)	38 ± 9	35 ± 10	0 ± 14	3 ± 8	36 ± 9	40 ± 11	11 ± 11	6 ± 8
	RFD (0-50ms) ($N.s^{-1}$)	2746 ± 1080*	845 ± 318*	2190 ± 2190	862 ± 948	2294 ± 824	1102 ± 339	1213 ± 1213	231 ± 319
	RFD (0-100ms) ($N.s^{-1}$)	3657 ± 1788¥	1570 ± 539	2396 ± 2396	1319 ± 1553	3058 ± 1376¥	1877 ± 415	1377 ± 1641	337 ± 436
	RFD (0-200ms) ($N.s^{-1}$)	3832 ± 1528	1821 ± 458	2118 ± 2118	829 ± 1498	3498 ± 1236	1894 ± 267	1781 ± 1781	4 ± 103
	RFD (0-300ms) ($N.s^{-1}$)	3005 ± 973*	1438 ± 230*	1649 ± 1649	509 ± 1101	3983 ± 1183§	1418 ± 129§	1852 ± 1852	52 ± 98
	RFD (0-400ms) ($N.s^{-1}$)	2379 ± 755*	1083 ± 148*	1340 ± 1340	338 ± 838	2352 ± 819§	1052 ± 80§	1481 ± 1481	41 ± 101
Con	Mean Bar v ($m.s^{-1}$)	0.51± 0.05	0.49 ± 0.11	0.07 ± 0.08	0.03 ± 0.06	0.57 ± 0.08§	0.55 ± 0.11§	0.09 ± 0.10	0.04 ± 0.05
	Peak F_v ($N.kg^{-1}$)	38 ± 3*	31 ± 27*	10 ± 10	1 ± 3	37 ± 3§	27 ± 4§	8 ± 8	1 ± 1
	Impulse ($N.kg^{-1}.s$)	36 ± 3	32 ± 12	2 ± 8	0 ± 4	33 ± 6§	29 ± 13§	4 ± 7	0 ± 4
	RFD (0-50ms) ($N.s^{-1}$)	2013 ± 737	816 ± 416	1131 ± 1131	311 ± 1046	2002 ± 1089	707 ± 166	1319 ± 1317	85 ± 283
	RFD (0-100ms) ($N.s^{-1}$)	3110 ± 1502	1391 ± 608	1695 ± 1922	344 ± 1634	3287 ± 1474	1258 ± 328	2084 ± 2084	98 ± 359
	RFD (0-200ms) ($N.s^{-1}$)	4070 ± 1791	1853 ± 624	2278 ± 2278	613 ± 1914	4205 ± 1850§	1623 ± 390§	2789 ± 2789	219 ± 360
	RFD (0-300ms) ($N.s^{-1}$)	3485 ± 1267	1712 ± 439	1859 ± 1859	601 ± 1292	3438 ± 1275§	1528. ± 338§	2130 ± 2130	186 ± 259
	RFD (0-400ms) ($N.s^{-1}$)	2707 ± 865*	1376 ± 324*	1418 ± 1419	494 ± 830	2579 ± 791§	1242 ± 283§	1536 ± 1536	151 ± 194

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; Ecc, Eccentric; Con, Concentric; RFD, Rate of force development; F_v, Vertical force; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.
* $p < 0.05$ OLY vs HBCON; § $p < 0.05$ POW vs LBCON; ¥ $p < 0.05$ OLY vs CON.

Table 15: Kinetic effect sizes and percentage differences 74–83% 1RM

		OLY vs HBCON		POW vs LBCON		OLY vs POW		HBCON vs LBCON	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v ($m.s^{-1}$)	0.3*	15.9	1.0^	40.2	0.3*	5.3	0.7§	12.7
	Peak F_v ($N.kg^{-1}$)	1.5^	43.7	1.9^	40.9	0.2*	1.3	0.4*	0.7
	Impulse ($N.kg^{-1}.s$)	0.0	6.3	0.8^	10.3	0.3*	4.8	0.6§	13.2
	RFD (0-50ms) ($N.s^{-1}$)	1.2^	224.8	0.9^	108.1	0.6§	19.7	0.7§	23.3
	RFD (0-100ms) ($N.s^{-1}$)	0.8^	132.9	0.6§	62.9	0.6§	19.6	0.7§	16.4
	RFD (0-200ms) ($N.s^{-1}$)	0.8^	110.4	0.9^	84.7	0.4*	9.6	0.0	3.8
	RFD (0-300ms) ($N.s^{-1}$)	1.0^	108.9	1.0^	110.3	0.3*	0.7	0.5§	1.4
	RFD (0-400ms) ($N.s^{-1}$)	1.0^	119.6	1.1^	123.5	0.3*	1.2	0.4*	3.0
Concentric	Mean Bar v ($m.s^{-1}$)	0.6§	2.4	0.6§	4.0	0.4*	11.9	0.8^	11.7
	Peak F_v ($N.kg^{-1}$)	1.6^	42.0	1.6^	37.6	0.2*	0.7	1.1^	2.5
	Impulse ($N.kg^{-1}.s$)	0.2*	12.4	0.4*	13.0	0.0	7.2	0.1	7.3
	RFD (0-50ms) ($N.s^{-1}$)	0.8^	146.7	0.7§	183.3	0.2*	0.6	0.3*	15.5
	RFD (0-100ms) ($N.s^{-1}$)	0.6§	123.6	0.8^	161.2	0.1	5.4	0.2*	10.5
	RFD (0-200ms) ($N.s^{-1}$)	0.7§	119.6	0.9^	159.1	0.2*	3.2	0.5§	14.2
	RFD (0-300ms) ($N.s^{-1}$)	0.8^	103.5	1.0^	125.0	0.3*	1.3	0.6§	12.0
	RFD (0-400ms) ($N.s^{-1}$)	0.9^	96.7	1.2^	107.7	0.4*	5.0	0.7§	10.9

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; ROM, F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 16: Kinetic results 84–93% 1RM

		High-Bar Back-Squat				Low-Bar Back-Squat			
Phase	Variable	OLY	HBCON	OLY vs HBCON Diff; ±90%CI	OLY vs POW Diff; ±90%CI	POW	LBCON	POW vs LBCON Diff; ±90%CI	HBCON vs LBCON Diff; ±90%CI
Ecc	Mean Bar v (m.s^{-1})	0.48 ± 0.09	0.39 ± 0.08	0.09 ± 0.19	0.00 ± 0.10	0.51 ± 0.10§	0.35 ± 0.10§	0.16 ± 0.16	0.04 ± 0.04
	Peak F_v (N.kg^{-1})	40 ± 3*	28 ± 5 *	10 ± 10	2 ± 3	38 ± 3§	27 ± 3§	10 ± 10	0 ± 3
	Impulse (N.kg^{-1}.s)	42 ± 7	42 ± 8	0 ± 14	0 ± 9	40 ± 9	47 ± 14	8 ± 14	6 ± 7
	RFD (0-50ms) (N.s^{-1})	2258 ± 943	857 ± 737	1088 ± 1188	517 ± 957	1857 ± 648§	493 ± 112§	1425 ± 1425	362 ± 745
	RFD (0-100ms) (N.s^{-1})	3413 ± 1587	1552 ± 1233	1727 ± 2147	715 ± 1648	2896 ± 1226§	950 ± 74§	1987 ± 1987	602 ± 1247
	RFD (0-200ms) (N.s^{-1})	3934 ± 1476	1813 ± 1295	1892 ± 2048	1203 ± 1572	2982 ± 1238§	1177 ± 161§	1889 ± 1889	633 ± 1306
	RFD (0-300ms) (N.s^{-1})	3204 ± 900*	1475 ± 712*	1648 ± 1648	799 ± 1122	2600 ± 1059§	1091 ± 256§	1627 ± 1627	384 ± 713
	RFD (0-400ms) (N.s^{-1})	2525 ± 601*	1163 ± 454*	1323 ± 1323	561 ± 780	2145 ± 803§	885 ± 228§	1381 ± 1381	278 ± 469
Con	Mean Bar v (m.s^{-1})	0.41 ± 0.06	0.40 ± 0.05	0.06 ± 0.06	0.00 ± 0.07	0.44 ± 0.09§	0.42 ± 0.09§	0.06 ± 0.08	0.03 ± 0.05
	Peak F_v (N.kg^{-1})	39 ± 4*	28 ± 5*	10 ± 10	2 ± 4	38 ± 3§	29 ± 4§	8 ± 8	1 ± 3
	Impulse (N.kg^{-1}.s)	48 ± 7	41 ± 8	2 ± 8	2 ± 9	46 ± 11§	42 ± 17§	1 ± 10	1 ± 6
	RFD (0-50ms) (N.s^{-1})	2278 ± 921	889 ± 324	1282 ± 1282	865 ± 1023	1617 ± 838	705 ± 243	1036 ± 1036	183 ± 333
	RFD (0-100ms) (N.s^{-1})	3303 ± 1632	1325 ± 674	1930 ± 1994	1024 ± 1727	2686 ± 1448§	964 ± 223§	1871 ± 1871	357 ± 719
	RFD (0-200ms) (N.s^{-1})	4255 ± 1608	1761 ± 956	2445 ± 2445	859 ± 1816	3757 ± 1598§	1289 ± 282§	2575 ± 2575	465 ± 993
	RFD (0-300ms) (N.s^{-1})	3715 ± 1018*	1639 ± 779*	2029 ± 2029	661 ± 1252	3245 ± 1150§	1250 ± 230§	2063 ± 2063	388 ± 841
	RFD (0-400ms) (N.s^{-1})	2897 ± 631*	1397 ± 565*	1456 ± 1456	528 ± 774	2491 ± 711§	1061 ± 254§	1515 ± 1515	335 ± 584

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; Ecc, Eccentric; Con, Concentric; RFD, Rate of force development; F_v, Vertical force; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.
* $p < 0.05$ OLY vs HBCON; § $p < 0.05$ POW vs LBCON.

Table 17: Kinetic effect sizes and percentage differences 84-93% 1RM

		OLY vs HBCON		POW vs LBCON		OLY vs POW		HBCON vs LBCON	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v (m.s^{-1})	0.3*	22.7	0.9^	46.0	0.0	6.1	0.9^	10.5
	Peak F_v (N.kg^{-1})	1.5^	42.5	2.1^	39.6	0.4*	4.3	0.1	2.1
	Impulse (N.kg^{-1}.s)	0.0	1.5	0.4*	14.8	0.0	5.4	0.9^	13.1
	RFD (0-50ms) (N.s^{-1})	0.7§	163.5	1.5^	276.5	0.4*	21.6	0.4*	73.7
	RFD (0-100ms) (N.s^{-1})	0.6§	119.9	1.1^	204.8	0.3*	17.8	0.4*	63.3
	RFD (0-200ms) (N.s^{-1})	0.7§	117.0	1.0^	153.3	0.5§	31.9	0.4*	54.0
	RFD (0-300ms) (N.s^{-1})	1.0^	117.2	1.1^	138.3	0.5§	23.2	0.5§	35.2
	RFD (0-400ms) (N.s^{-1})	1.2^	17.2	1.2^	142.5	0.5§	17.7	0.5§	31.4
Concentric	Mean Bar v (m.s^{-1})	0.7§	5.5	0.5§	5.1	0.0	6.8	0.4*	7.7
	Peak F_v (N.kg^{-1})	1.3^	39.7	1.6^	32.0	0.4*	3.6	0.3*	2.1
	Impulse (N.kg^{-1}.s)	0.2*	18.1	0.1	11.1	0.1	4.4	0.2*	1.8
	RFD (0-50ms) (N.s^{-1})	0.8^	156.3	0.9^	129.2	0.6§	40.9	0.5§	26.0
	RFD (0-100ms) (N.s^{-1})	0.7§	149.3	0.9^	178.6	0.4*	23.0	0.4*	37.4
	RFD (0-200ms) (N.s^{-1})	0.9^	141.7	1.1^	191.4	0.3*	13.3	0.4*	36.6
	RFD (0-300ms) (N.s^{-1})	1.1^	126.7	1.2^	159.6	0.4*	14.5	0.4*	31.1
	RFD (0-400ms) (N.s^{-1})	1.2^	107.4	1.4^	134.8	0.5§	16.3	0.5§	31.6

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; ROM, F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 18: Kinetic results 94–99% 1RM

		High-Bar Back-Squat				Low-Bar Back-Squat			
Phase	Variable	OLY	HBCON	OLY vs HBCON Diff; ±90%CI	OLY vs POW Diff; ±90%CI	POW	LBCON	POW vs LBCON Diff; ±90%CI	HBCON vs LBCON Diff; ±90%CI
Ecc	Mean Bar v (m.s^{-1})	0.47 ± 0.09	0.36 ± 0.10	0.12 ± 0.15	0.04 ± 0.13	0.45 ± 0.12	0.34 ± 0.07	0.10 ± 0.14	0.03 ± 0.07
	Peak F_v (N.kg^{-1})	41 ± 4*	29 ± 4*^	11 ± 11	2 ± 4	39 ± 3§	28 ± 3§^	11 ± 11	1 ± 1
	Impulse (N.kg^{-1}.s)	44 ± 7	46 ± 11	4 ± 14	6 ± 12	49 ± 13	49 ± 7	2 ± 14	3 ± 9
	RFD (0-50ms) (N.s^{-1})	2018 ± 1110	811 ± 500	1272 ± 1479	383 ± 1275	1618 ± 1107	687 ± 140	893 ± 1207	123 ± 504
	RFD (0-100ms) (N.s^{-1})	2953 ± 1658	1413 ± 957	1344 ± 2274	477 ± 1665	2371 ± 1266	1071 ± 402	1302 ± 1418	300 ± 848
	RFD (0-200ms) (N.s^{-1})	3532 ± 1817	1608 ± 912	1509 ± 2399	392 ± 1864	3061 ± 1445	1158 ± 619	1932 ± 1932	440 ± 622
	RFD (0-300ms) (N.s^{-1})	3031 ± 1224	1270 ± 593	1535 ± 1622	316 ± 1484	2708 ± 1350	962 ± 396	1801 ± 1801	300 ± 399
	RFD (0-400ms) (N.s^{-1})	2455 ± 754*	958 ± 474*	1314 ± 1314	262 ± 1039	2174 ± 1035	717 ± 269	1464 ± 1464	242 ± 346
Con	Mean Bar v (m.s^{-1})	0.32 ± 0.03*	0.31 ± 0.05*	0.06 ± 0.06	0.02 ± 0.05	0.31 ± 0.05§	0.31 ± 0.04§	0.01 ± 0.06	0.02 ± 0.03
	Peak F_v (N.kg^{-1})	41 ± 5*	29 ± 4*	11 ± 11	2 ± 4	39 ± 3	30 ± 4	9 ± 9	1 ± 1
	Impulse (N.kg^{-1}.s)	62 ± 3	54 ± 14	2 ± 11	6 ± 10	69 ± 12§	55 ± 10§	11 ± 14	1 ± 7
	RFD (0-50ms) (N.s^{-1})	2083 ± 906	706 ± 525	992 ± 1154	327 ± 935	1595 ± 818	575 ± 342	1016 ± 1016	141 ± 294
	RFD (0-100ms) (N.s^{-1})	3425 ± 1412	1062 ± 815	1880 ± 1880	498 ± 1481	2761 ± 1258§	870 ± 461§	1866 ± 1866	224 ± 542
	RFD (0-200ms) (N.s^{-1})	4358 ± 1500*	1441 ± 971*	2605 ± 2605	560 ± 1710	3661 ± 1534§	1103 ± 545§	2491 ± 2491	335 ± 728
	RFD (0-300ms) (N.s^{-1})	3778 ± 1088*	1376 ± 811*	2221 ± 2221	452 ± 1347	3249 ± 1275§	1043 ± 478§	2171 ± 2171	421 ± 606
	RFD (0-400ms) (N.s^{-1})	2905 ± 767*	1188 ± 578*	1639 ± 1639	329 ± 993	2532 ± 963§	913 ± 372§	1626 ± 1626	247 ± 449

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; Ecc, Eccentric; Con, Concentric; RFD, Rate of force development; F_v, Vertical force; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.
* $p < 0.05$ OLY vs HBCON; § $p < 0.05$ POW vs LBCON; ^ $p < 0.05$ HBCON vs LBCON.

Table 19: Kinetic effect sizes and percentage differences 94–99% 1RM

		OLY vs HBCON		POW vs LBCON		OLY vs POW		HBCON vs LBCON	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v (m.s^{-1})	0.6§	27.9	0.5§	33.5	0.2*	2.4	0.4*	6.4
	Peak F_v (N.kg^{-1})	1.2^	43.9	2.0^	41.5	0.3*	4.2	1.3^	2.4
	Impulse (N.kg^{-1}.s)	0.2*	4.5	0.1	0.3	0.3*	9.5	0.4*	5.8
	RFD (0-50ms) (N.s^{-1})	0.6§	148.9	0.5§	135.6	0.2*	24.7	0.2*	18.0
	RFD (0-100ms) (N.s^{-1})	0.4*	109.0	0.7§	121.4	0.2*	24.5	0.3*	31.9
	RFD (0-200ms) (N.s^{-1})	0.5§	119.6	0.8^	164.2	0.1	15.4	0.6§	38.8
	RFD (0-300ms) (N.s^{-1})	0.7§	138.7	0.9^	181.4	0.1	11.9	0.7§	32.0
	RFD (0-400ms) (N.s^{-1})	0.9^	156.1	0.9^	203.1	0.2*	12.9	0.6§	33.6
Concentric	Mean Bar v (m.s^{-1})	1.2^	5.5	0.1	1.1	0.3*	3.9	0.5§	2.7
	Peak F_v (N.kg^{-1})	1.2^	42.4	1.6^	32.1	0.3*	4.1	0.7§	3.5
	Impulse (N.kg^{-1}.s)	0.1	15.9	0.6§	25.7	0.4*	10.2	0.1	2.7
	RFD (0-50ms) (N.s^{-1})	0.6§	195.0	0.8^	177.6	0.6§	30.6	0.4*	22.9
	RFD (0-100ms) (N.s^{-1})	0.7§	222.3	0.9^	217.2	0.2*	24.0	0.4*	22.1
	RFD (0-200ms) (N.s^{-1})	0.9^	202.3	1.0^	231.8	0.2*	19.0	0.4*	30.6
	RFD (0-300ms) (N.s^{-1})	1.0^	174.5	1.1^	211.4	0.2*	16.3	0.7§	31.9
	RFD (0-400ms) (N.s^{-1})	1.1^	144.5	1.1^	177.4	0.2*	14.7	0.5§	30.1

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; ROM, F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 20: Kinetic results 100% 1RM

Phase	Variable	High-Bar Back-Squat OLY	HBCON	OLY vs HBCON Diff; ±90%CI	OLY vs POW Diff; ±90%CI	Low-Bar Back-Squat POW	LBCON	POW vs LBCON Diff; ±90%CI	HBCON vs LBCON Diff; ±90%CI
Ecc	Mean Bar v (m.s^{-1})	0.48 ± 0.09*	0.34 ± 0.09*	0.14 ± 0.14	0.03 ± 0.11	0.44 ± 0.14§	0.31 ± 0.06§	0.14 ± 0.14	0.04 ± 0.07
	Peak F_v (N.kg^{-1})	42 ± 4*	29 ± 4*	13 ± 13	2 ± 3	40 ± 2§	29 ± 3§	11 ± 11	0 ± 2
	Impulse (N.kg^{-1}.s)	44 ± 9	50 ± 11	6 ± 11	7 ± 11	51 ± 11	56 ± 7	5 ± 12	5 ± 10
	RFD (0-50ms) (N.s^{-1})	2240 ± 852*	634 ± 372*	1606 ± 1606	490 ± 905	1750 ± 878§	375 ± 337§	1375 ± 1375	258 ± 413
	RFD (0-100ms) (N.s^{-1})	3062 ± 1681	1052 ± 650	2010 ± 2010	406 ± 1660	2656 ± 1485§	676 ± 581§	1980 ± 1980	376 ± 769
	RFD (0-200ms) (N.s^{-1})	3535 ± 1767*	1220 ± 872*	2315 ± 2315	412 ± 1931	3123 ± 1920§	801 ± 413§	2322 ± 2322	419 ± 832
	RFD (0-300ms) (N.s^{-1})	2984 ± 1233*	1012 ± 478*	1971 ± 1971	334 ± 1417	2650 ± 1464§	819 ± 342§	1831 ± 1831	193 ± 534
	RFD (0-400ms) (N.s^{-1})	2417 ± 823*	824 ± 360*	1593 ± 1593	224 ± 993	2193 ± 1060§	666 ± 325§	1528 ± 1528	159 ± 408
Con	Mean Bar v (m.s^{-1})	0.22 ± 0.03	0.20 ± 0.03	0.02 ± 0.04	0.01 ± 0.05	0.21 ± 0.06	0.23 ± 0.05	0.03 ± 0.07	0.04 ± 0.06
	Peak F_v (N.kg^{-1})	41 ± 4*	30 ± 3*	12 ± 12	2 ± 4	40 ± 2§	31 ± 3§	9.00 ± 9.00	1 ± 2
	Impulse (N.kg^{-1}.s)	96 ± 11	85.86 ± 18.30	10 ± 17	14 ± 23	110 ± 29	75 ± 15	35 ± 35	12 ± 23
	RFD (0-50ms) (N.s^{-1})	1734 ± 916*	629 ± 248*	1105 ± 1105	86 ± 1197	1820 ± 1332	507 ± 222	1313 ± 1313	122 ± 179
	RFD (0-100ms) (N.s^{-1})	3218 ± 1572*	1049 ± 480*	2169 ± 2169	202 ± 1972	3016 ± 2153	676 ± 254	2341 ± 2341	374 ± 528
	RFD (0-200ms) (N.s^{-1})	4310 ± 1678*	1323 ± 685*	2987 ± 2987	598 ± 1933	3712 ± 2002§	998 ± 420§	2714 ± 2714	325 ± 504
	RFD (0-300ms) (N.s^{-1})	3745 ± 1123*	1251 ± 603*	2494 ± 2494	449 ± 1325	3296 ± 1394§	1034 ± 438§	2262 ± 2262	217 ± 522
	RFD (0-400ms) (N.s^{-1})	2911 ± 729*	1041 ± 428*	1871 ± 1871	369 ± 866	2543 ± 917§	890 ± 413§	1653 ± 1653	151 ± 493

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; Ecc, Eccentric; Con, Concentric; RFD, Rate of force development; F_v, Vertical force; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.

* $p < 0.05$ OLY vs HBCON; § $p < 0.05$ POW vs LBCON.

Table 21: Kinetic effect sizes and percentage differences 100% 1RM

		OLY vs HBCON		POW vs LBCON		OLY vs POW		HBCON vs LB CON	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v (m.s^{-1})	0.9^	40.0	0.9^	46.4	0.2*	7.7	0.5§	11.2
	Peak F_v (N.kg^{-1})	1.9^	44.8	2.9^	39.7	0.3*	3.5	0.2*	0.2
	Impulse (N.kg^{-1}.s)	0.4*	11.8	0.3*	9.3	0.4*	12.6	0.5§	11.2
	RFD (0-50ms) (N.s^{-1})	1.3^	253.5	1.1^	366.4	0.4*	28.0	0.5§	68.9
	RFD (0-100ms) (N.s^{-1})	0.8^	191.1	0.9^	292.9	0.2*	15.3	0.4*	55.6
	RFD (0-200ms) (N.s^{-1})	0.9^	189.8	0.9^	289.8	0.1	13.2	0.4*	52.3
	RFD (0-300ms) (N.s^{-1})	1.1^	197.7	0.9^	223.4	0.2*	12.6	0.3*	23.5
	RFD (0-400ms) (N.s^{-1})	1.4^	193.2	1.0^	229.5	0.2*	10.2	0.3*	23.9
Concentric	Mean Bar v (m.s^{-1})	0.4*	9.9	0.3*	10.6	0.1	4.5	0.5§	17.7
	Peak F_v (N.kg^{-1})	1.7^	39.3	2.1^	29.2	0.3*	3.2	0.7§	4.5
	Impulse (N.kg^{-1}.s)	0.4*	11.6	0.8^	46.9	0.4*	12.6	0.4*	13.1
	RFD (0-50ms) (N.s^{-1})	0.9^	175.6	0.7§	259.1	0.0	4.7	0.6§	24.1
	RFD (0-100ms) (N.s^{-1})	1.0^	206.7	0.8^	346.5	0.1	6.7	0.6§	55.3
	RFD (0-200ms) (N.s^{-1})	1.3^	225.8	1.0^	271.8	0.2*	16.1	0.6§	32.5
	RFD (0-300ms) (N.s^{-1})	1.5^	199.3	1.2^	218.7	0.2*	13.6	0.4*	21.0
	RFD (0-400ms) (N.s^{-1})	1.7^	179.8	1.3^	185.8	0.3*	14.5	0.3*	17.0

OLY, Olympic weightlifters; POW, Powerlifters; HBCON, Control high-bar back-squat; LBCON, Control low-bar back-squat; ROM, F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

(Tables 14, 16, 18, ands 20). In all cases of significant difference, the more experienced OLY and POW groups produced larger forces than those produced by the less experienced HBCON and LBCON groups respectively.

Discussion

The purpose of this study was to compare and contrast the differences in kinematics and kinetics between the HBBS and LBBS in order to understand why the LBBS typically allows for greater loads to be lifted (O'Shea, 1985). Originally the HBBS and LBBS were compared by combining experienced populations (OLY and POW) with the same bar position in resistance trained individuals (HBCON and LBCON). However, initial analyses revealed differences between groups using the same bar position (i.e. between HBCON and OLY, and LBCON and POW, respectively). Therefore, each group was compared independently in order to examine the kinematic and kinetic differences that arise as a function of bar position (i.e. high-bar and low-bar position) and experience level (i.e. OLY high-bar vs. POW low-bar).

To the best of our knowledge, this is the first study to compare the kinematic and kinetic differences of the HBBS and LBBS using loads ≥ 90%1RM. The main findings of this investigation were; 1) statistically significant results were observed in both joint angles and kinetics between the OLY and HBCON, and POW and LBCON groups; 2) although not significant, a small effect size indicated that greater loads were lifted for each of the percentage 1RM ranges for the LBBS when comparing the POW vs OLY (d = 0.2-0.3). In addition, small (d ≥ 0.2) and moderate (d ≥ 0.5) effect sizes indicated that the LBCON group lifted greater loads and loads relative to body weight across all ranges of %1RM; 3) no significant differences were observed between the OLY and POW groups in either kinematics or kinetics, under any condition. However, small (d ≥ 0.2), moderate (d ≥ 0.5) and large (d ≥ 0.8) effects were observed across all ranges of load between OLY and POW; 4) significantly larger joint angles were observed on the HBCON, in comparison to the LBCON in knee ROM at 74-83% and 100 % 1RM, peak flexion at 84-93%, 94-99% and 100% 1RM. The LBCON however did produced a larger knee flexion angle at 100% 1RM, than the HBCON; 5) only one significant difference was observed between the HBCON and LBCON groups in kinetics. The HBCON group produced a significantly larger peak F_v at 94-99% 1RM in the eccentric phase.

Surprisingly, no significant differences were observed between the experienced OLY and POW groups for any joint angles. It was expected that the OLY would display a greater angle at peak hip flexion due to the more upright torso position, and a smaller knee flexion angle. In the present study, small to moderate magnitudes of effect ($d \geq 0.2$-0.5) were observed at all four percentages of 1RM, indicating that the OLY group demonstrated a larger hip angle displayed at peak flexion by the OLY group at all percentages of 1RM tested. Prior research by Fry et al., (1993) and Wretenberg et al., (1996) demonstrated a larger hip angle in the HBBS, and a greater forward lean in the LBBS. However, the squats were only performed at 50% and 65% 1RM, respectively, in these aforementioned studies and the results also failed to reach statistical significance. Therefore, it is possible to surmise that OLY consistently demonstrate a larger hip angle and therefore, a more upright torso position when performing the HBBS when compared to the LBBS performed by POW. The knee joint findings of the present study were similar to those reported in other studies (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2001; Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Han, Ge, Liu, & Liu, 2013; Hooper et al., 2014; Kobayashi et al., 2010; McKean, Dunn, & Burkett, 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; van den Tillaar, Andersen, & Saeterbakken, 2014) and it appears that the OLY displays a smaller peak knee flexion angle (i.e. greater depth) than what is seen during the POW. However, the difference was not pronounced, as there were no significant differences observed but there were small to moderate magnitudes of change ($d \geq 0.2$–0.5).

Interestingly however, significant differences were observed in the hip and knee joints, between the HBBS performed by the HBCON group, and the LBBS performed by the LBCON. The significant differences between these two groups in joint angles are in line with the prior literature, and this indicates that there may have been an influence of experience on the significant results in this study and in the findings or previous research. The smaller hip angle, and greater knee angle shown by the POW group in the present study, indicate a greater posterior displacement of the hip, a more vertical shank, and therefore a greater ankle angle. However, the present study showed no significant differences in ankle joint angles between the OLY and POW groups. Instead, only one significant difference was presented, in the ankle ROM between OLY and HBCON at 100% 1RM ($d = 0.7$; % Diff = 18.3). Previous investigations have shown no definitive differences between the ankle joint angles of the HBBS and LBBS (Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Kobayashi et al., 2010; Sato, Fortenbaugh, & Hydock, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). The ankle joint angle results of this study further support these previous findings between experienced populations (i.e. OLY and POW), but may indicate differences in an experienced versus less-experienced groups HBBS practitioners (i.e. OLY and HBCON) at maximal effort.

The centre of pressure is the point on the ground at which the vertical GRF vector originates (Benda, Riley, & Krebs, 1994). The upper body has a larger mass than the lower body (Chiu, 2009), and therefore humans are inherently unstable, and require effective control mechanisms to constantly resist perturbation (Winter, 1995). This inherent instability is expressed in three planes of motion when load is added to the upper body via a barbell, as in the case of the HBBS and/or LBBS (Schick et al., 2010). The results of this study indicate that the mechanisms that the body employs to maintain the balance of its system are concentrated at the hip and not at the knee or ankle joint. At the deepest part of each squat, this study found the distance of the bar behind the centre of pressure (COP) was larger in the LBBS (55 ± 39 mm) than in the HBBS (21 ± 36 mm) (Table 11). These findings exemplify the effects of the low-bar position being further down the back on the lower trapezius musculature, and also indicates a more vertical torso in the HBBS. In order to maintain the position of the barbell on the shoulders and to keep the body's centre of mass within the base of support (BOS), the lifter must adopt a smaller torso angle when performing the LBBS. In addition, a wider stance is also often employed when performing the LBBS (Chandler & Stone, 1992; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001) and anecdotally it is performed to suit the hip structure of the lifter to allow them to obtain the required depth. An increased stance width also acts to effectively increase the BOS, and therefore allows for the bar to be a further distance from the COP, without exiting the BOS. Thus, the smaller hip angle demonstrated in this study may allow greater loads to be lifted by the LBBS, due to the decreased moment arm, greater emphasis on the strong hip musculature, as well as the aforementioned increased stability (Sato, Fortenbaugh, & Hydock, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012).

No significant differences in kinetic results were observed between the OLY and POW groups. However, small ($d \geq 0.2$) and moderate ($d \geq 0.5$) magnitudes of change were observed for several variables (Tables 15, 17, 19, and 21). The OLY and POW that took part in this study were all of a high level and consequently, they lifted loads that were similar to each other when presented relative to body weight, but not in terms of actual load (Table 9 and 10). Although not statistically significant, the POW on average lifted greater loads for each percentage of 1RM. Prior research has shown that as load is increased, there is a resulting increase in the F_v produced that is proportionate to the increase in load (Ebben &

Jensen, 2002; Ebben et al., 2012; Flanagan & Salem, 2007; Kellis, Arambatzi, & Papadopoulos, 2005; Zink, Perry, Robertson, Roach, & Signorile, 2006). With this in mind, it was expected that the results of this study would show that the POW had the ability to generate greater F_v levels during the LBBS, due to the larger loads typically lifted. However, this did not occur. Instead, no significant differences were observed between the POW and OLY groups, but only small effects (d ≥ 0.2) for F_v. These effects are also in direct contrast to Goodin (2015), who showed the HBBS to produce larger F_v, when compared to the LBBS, with loads of 20-80% 1RM, in HBBS dominant athletes. In the current investigation the F_v levels were only shown to be significantly greater in the LBBS than the HBBS between the less experienced HBCON and LBCON groups in the eccentric phase at 94-99% 1RM ($p < 0.05$; d = 1.3; % Diff = 2.4). This indicates that the LBBS may in fact be a more efficient technique of squatting large loads in proportion to the lifter's bodyweight. Even though greater loads were lifted by the POW, when compared to the OLY for each set, the F_v produced was relatively the same, thus the mechanical advantage can be attributed to kinematic joint angle differences. An analysis of the lower limb and trunk muscle activity throughout the squat for both the HBBS and LBBS is necessary to supplement these conclusions. Such an analysis will create a greater understanding as to the level of muscle mass that is deemed to be active throughout each squat style. These findings may provide an insight into the reasons for differing kinetic results, through muscle activity results.

The resistance trained males in this study were recruited as a control group and they did not have any specific expertise in either the HBBS or LBBS. As a result, the techniques displayed by the control group had many significant kinetic differences when compared with the well-trained OLY and POW athletes (Tables 14-21). In addition, significant differences were also observed in several joint angles between the OLY and POW groups versus the HBCON and LBCON groups (Table 12 and 13). Therefore, it can be concluded that resistance training experience and technical proficiency have a strong influence on the associated joint angle kinematics and kinetics. Thus, the level of experience of an individual may be a useful predictor of squatting technical performance. This notion, and the results of this study are supported the work of Miletello, Beam and Cooper (2009) which reported differences in kinematic variables measured at the knee when three different POW groups, of varying experience, performed the LBBS. In order of highest skill to least skilled, the POW groups were: competitive collegiate; competitive high school; and novice. When performing a maximal squat, Miletello, Beam and Cooper (2009) showed a direct correlation to between performance and skill level. The most significant finding presented by these investigators was that the POW with a higher skill level displayed greater acceleration after reaching peak flexion (maximum depth), and beginning to return to full extension (upright position). This result is echoed in the present study, where significantly greater ($p < 0.05$) mean bar velocities were observed in the POW group, when compared to the LBCON group at 74-83% 1RM ($d = 0.5$; % Diff = 4.0), 84-93% 1RM ($d = 0.4$; % Diff = 5.1), and 94-99% 1RM ($d = 0.1$; % Diff = 1.1). A significantly larger mean bar velocity was also observed in the OLY group, when compared to the HBCON at 94-99% 1RM ($d = 1.0$; % Diff = 5.5). Future studies should look to specifically only include well trained athletes when comparing the HBBS to LBBS, in order to minimise the dilution of results from less experienced populations.

The significant differences observed between the experienced (i.e. OLY and CON) groups and the less experienced (i.e. HBCON and LBCON) groups, indicates that the time spent familiarizing each control participant with both squat styles was insufficient to create expertise in both styles prior to testing. The differences in joint angles between the two bar positions in the control group, can also be attributed to a lack of expertise in both squat styles. Another limitation to this study was the low number of participants representing each group, as this reduced the statistical power of the model. Athletes competing at a high level were targeted to make up the experienced OLY and POW groups (i.e. international and national level, respectively). Therefore, the pool of potential participants was automatically reduced. Moreover, athletes were also recruited from different gyms, in different stages of competition preparation at the time of testing. As a result of the reduced sample size, the effect size data should be carefully considered rather than interpreting the findings based on statistical significance alone. Future studies should look to compare larger cohorts of experienced HBBS and LBBS participants up to and including 100% of 1RM, with the further addition of muscle activity analysis, in order to complete a full profile of each squat style and improve statistical power.

Practical applications

This study provided evidence to suggest that the LBBS is a more efficient way of squatting large loads, as demonstrated by comparable kinetic results to the HBBS despite greater absolute loads being lifted. This study also indicates that resistance trained individuals should not be compared/combined with well-trained athletes when comparing such a technical movement as the HBBS or LBBS as there is an apparent influence of expertise on the performance of these techniques. With regards to training adaptations, practitioners seeking to place emphasis on the stronger hip musculature should consider the LBBS, as the greater forward lean of the movement ensures the hip muscles are engaged more so than the HBBS. It is also recommended that when the goal is to lift the greatest load possible, the LBBS may be preferable. Conversely, the HBBS is more suited to replicate movements that exhibit a more upright torso position, such as the snatch and clean or to place more emphasis on the associated musculature of the knee joint.

CHAPTER FOUR - The high-bar back-squat and the competition Olympic weightlifts: A kinematic and kinetic comparison

Preface

This chapter is an original investigation into the kinematic, and kinetic differences between the HBBS and snatch and clean in Olympic weightlifters. As previously mentioned, the HBBS is commonly used by Olympic weightlifters to simulate the catch position of the Olympic weightlifting competition lifts; the snatch and clean and jerk (Wretenberg, Feng, & Arborelius, 1996). However, the prescription of the HBBS as a supplementary exercise to the snatch and clean is based off anecdotal coaching evidence. To date, no study has completed a kinematic and/or kinetic comparison between the three lifts in question. Therefore, the purpose of this study is to fill this gap in the current literature and investigate the validity of the HBBS as supplementary to the snatch and clean.

Introduction

In the sport of Olympic weightlifting, athletes are required to lift a weighted barbell from a starting position on the floor to a finishing position overhead. The two lifts that are performed in competition are the snatch, and the clean and jerk. The snatch technique is performed by lifting the barbell from the ground to the overhead finishing position in one continuous movement (using a wide grip) (Garhammer, 1989). The clean and jerk on the other hand is performed in two parts; the clean, and the jerk. The clean is performed by lifting the barbell in one continuous motion from the ground, to a stationary position on the front of the shoulders (using a shoulder-width grip) (Storey & Smith, 2012). The jerk is performed by moving the barbell from its stationary position on the front of the shoulders to the finishing position overhead (Storey & Smith, 2012). Each athlete is given three attempts at both the snatch and clean and jerk, with the greatest load lifted in each lift being added together to create the lifter's 'total'. Within each weight class, the athlete with the greatest 'total' is declared the winner or in cases where two lifters finish on the same total, the lightest lifter wins.

When performing the two competition lifts, Olympic weightlifters produce power outputs unrivalled by other sports (Garhammer, 1980). Furthermore, in Olympic weightlifting, muscular force must be developed quickly (<200ms) in order to complete each lift successfully (Storey, Wong, Smith, & Marshall, 2012; Wilson, Lyttle, Ostrowski, & Murphy, 1995). Each lift requires a great level of technical proficiency, and as such a large proportion of Olympic weightlifting training focuses on the technical elements of the two competition lifts (Storey & Smith, 2012). However, there are a variety of complementary and supplementary exercises that are included in the typical training regimes of these athletes. The aim of these exercises is to increase both general and specific strength, and power, with the goal of transferring these qualities to the two competition lifts.

One such complementary exercise of interest is the back-squat. The back-squat is performed with a barbell placed posteriorly to the shoulders, across the trapezius musculature (Gullett, Tillman, Gutierrez, & Chow, 2009), and is commonly regarded as a fundamental movement for the assessment, and improvement of lower limb muscle strength, function, and resilience to injury (Comfort, Stewart, Bloom, & Clarkson, 2014; Cormie, McGuigan, & Newton, 2010b; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; McCaw & Melrose, 1999; Senter & Hame, 2006). This is due to the major contributions of the lower limb and trunk musculature to perform the movement (Escamilla, 2001; Maddigan, Button, & Behm, 2014;

Robertson, Wilson, & Pierre, 2008). While the back-squat is considered a fundamental training-lift for Olympic weightlifters, at no point in the snatch, or clean and jerk is the bar placed posteriorly to the shoulder such as it is in the back-squat. Despite the lack of similarity with regard to the bar position, the back-squat is still commonly used as a means of strengthening the lower limb and trunk musculature.

The back-squat itself, is split into two different styles according to where the bar is positioned on the trapezius musculature. The high-bar back-squat (HBBS) is performed with the barbell placed across the top of the trapezius, just below the process of the C7 vertebrae. Conversely, the low-bar back-squat (LBBS) places the barbell on the lower trapezius, just over the posterior deltoid and along the spine of the scapula (Wretenberg, Feng, & Arborelius, 1996). The HBBS is the preferred back squat variation used by Olympic weightlifters, as this movement has apparent similarities to the catch position of the snatch and the clean (Wretenberg, Feng, & Arborelius, 1996). For example, the HBBS is defined by an upright torso (Benz, 1989; Fry, Aro, Bauer, & Kraemer, 1993; Wretenberg, Feng, & Arborelius, 1996) and a greater knee flexion resulting in a 'deep' squat depth (Donnelly, Berg, & Fiske, 2006; Escamilla et al., 2001; Flanagan & Salem, 2007; Hales, Johnson, & Johnson, 2009; Han, Ge, Liu, & Liu, 2013; Hooper et al., 2014; Kobayashi et al., 2010; McKean, Dunn, & Burkett, 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; van den Tillaar, Andersen, & Saeterbakken, 2014), such as is displayed at the catch position of both the snatch and clean. However, on closer inspection of the existing kinematic data, the snatch is shown to display a deeper catch position than the depth typically reached at peak knee flexion in the HBBS (Campos, Poletaev, Cuesta, Pablos, & Carratalá, 2006; Gourgoulis et al., 2002).

To date, no study has specifically compared the HBBS to the snatch and the clean and jerk to determine if a kinematic and/or a kinetic transference exists between HBBS and these competition lifts. Thus, the purpose of this study is to compare and contrast the kinematics and kinetics of the HBBS with those of the snatch and clean in competitive Olympic weightlifters.

Methods

Experimental approach to the problem

A cross-sectional design was used to quantify the joint angle and GRF differences between the HBBS, the snatch and clean in competitive Olympic weightlifters, up to and including 100% of one repetition maximum (1RM).

The same Olympic weightlifters from Chapter three were used in this study. After the squat testing session, participants returned to the laboratory for a second session in which the snatch and clean and jerk were tested. Only the clean part to the lift was analysed as it bears the closest resemblance to the HBBS.

Participants

Six male Olympic weightlifters (height: 176.7 ± 7.7 cm; bodyweight: 83.1 ± 13 kg; age: 25.3 ± 3.1 years) who had previously qualified for national championship level competition volunteered to participate in this study. All participants routinely performed the HBBS in training. All participants were free of injury and had ≥ 1 year's strength training experience (3.75 ± 2.72 years) consisting of ≥ 3 training sessions per week. Prior to testing, written informed consent was received from each participant and all testing conditions were examined and approved by the Auckland University of Technology Ethics Committee (14/398).

Testing sessions

The Olympic weightlifters were required to attend two testing sessions separated by seven days. Session one comprised of a full level two anthropometric assessment by an experienced ISAK anthropometrist, followed by a 1RM test of the HBBS. The second session comprised of a 1RM test of both the snatch and clean and jerk.

Back-squat 1 RM test procedures

The Olympic weightlifting participants were instructed to squat to the usual depth that they perform in training through a bending of the knees, and then ascend in a fluid motion to an upright stance with knees locked, without the aid of any spotters. Specific focus was placed on ensuring the legs were completely locked out at the conclusion of each repetition, and no downward movement was observed on the ascent.

Each participants beltless 1RM was estimated prior to testing. If in normal training, the participant did not use a weight belt, the athlete's current beltless 1RM was used. If the participant used a weight belt in normal training, and had a known belted 1RM, this belted 1RM was used to predict the athlete's beltless 1RM. The beltless 1RM was shown to be approximately 90% of a belted 1RM, though pilot testing. Weightlifting shoes (comprised of a hard sole and slightly raised heel), as commonly worn by Olympic weightlifters, were required to be worn by all participants, and the heel height was required to be within the range of 1.5-2.0 centimetres. The only supportive aids allowed to be worn during the testing, were wrist wraps. Before all testing procedures, each participant completed a standardized dynamic warm up consisting of: 1) 10 leg swings front and back, 2) 10 trunk twists, 3) 10 body weight squats, 4) 10 press-ups, 5) 10 wrist rotations clockwise, and 10 rotations anti-clockwise, 6) 5 'T' shoulder movements, and 7) 5 'Y' shoulder movements (Appendix 6).

The 1RM testing protocol was adapted from Matuszak et al. (2003), and consisted of the participants performing 8 repetitions at 50% of the predicted 1 repetition maximum (RM), 3 repetitions at 60%, 2 repetitions at 70%, and 1 repetition at 80, and 90%. In line with each participant's normal warm up procedure, a small number ($\leq$ 3) of additional warm up sets were permitted prior to the initial 8 repetition set with 50% 1RM. After the 90% of predicted 1RM lift, the participant was consulted as to what weight they would like to attempt for a maximal 1RM lift. A Gymaware Powertool (Kinetic Performance Technology, Canberra, Australia), was used to measure mean concentric velocity for immediate feedback. The mean concentric velocity, and the input of an experienced strength coach assisted athletes in attempt selection to get as close to a true 1RM as possible (Zourdos et al., 2015). A lift at 95% 1RM was commonly performed prior to the predicted maximal 1RM attempt. After each successful attempt, small weight increments (1-5 kg) were made in order to obtain a true maximum. Between 3 and 5 minutes' rest was allowed between sets before the next weight was attempted.

Snatch and clean 1 RM test procedures

The snatch and clean attempts were completed in line with the 2013-2016 International Weightlifting Federation Technical and Competition rules (International Weightlifting Federation, 2015). The snatch was deemed to be successful if the athlete was able to lift the barbell from a starting position from the floor to a straight-arm overhead receiving position in one continuous movement. Conversely the clean was deemed successful if the athlete was able to move the bar from a starting position from the floor to a final position with the bar resting on the front of the shoulders. In both the snatch and clean, the participants were required to catch the barbell in a full squat position before ascending to a full motionless standing position.

The weight increments for the 1RM testing protocol were based on each participant's current snatch and clean and jerk 1RM (performed within the last six months). Weightlifting shoes were required to be worn and no other supportive aids beyond the use of wrist wraps were permitted. The same dynamic warm up as described in the back-squat protocol was completed.

The 1RM testing protocol for both the snatch and clean was adapted from Storey, Birch, Fan, and Smith (2015) and consisted of 3 repetitions at 50% and 60% of predicted 1RM, 2 repetitions at 70%, and then 1 repetition at 80%, 85%, 90%, 95%, and 100% of the predicted 1RM. If any attempt was deemed to be unsuccessful, the load would remain the same and the participant was allowed no more than two further attempts at that load to achieve a successful lift (a maximum of three attempts in total). If the participant was not able to complete a successful lift within three attempts, the previously completed load was deemed to be the maximum. Subsequent load increases were only attempted following a successful lift. Each set was separated by between 2 and 3 minutes of rest (Storey, Birch, Fan, & Smith, 2015). Once the predicted 100% of 1RM had been reached, the athlete was consulted, and small increases (1-5 kg) were made in weight in order to find a true maximum. Once the snatch 1RM had been achieved, the participants were then given 10 minutes rest before starting the clean and jerk 1RM test as is done in competition (Storey, Birch, Fan, & Smith, 2015).

Biomechanical instrumentation

Two embedded force platforms (Model AM6501, Bertec Corp., Columbus, Ohio, USA), were arranged next to each other in the middle of the laboratory, and used to collect all kinetic squat data at a sampling rate of 1000Hz. The kinetic variables of interest included mean bar velocity ($m \cdot s^{-1}$); peak F_v ($N \cdot kg^{-1}$); impulse ($N \cdot kg^{-1} \cdot s$); RFD (0-50ms) ($N \cdot s^{-1}$); RFD (0-100ms) ($N \cdot s^{-1}$); RFD (0-200ms) ($N \cdot s^{-1}$); RFD (0-300ms) ($N \cdot s^{-1}$); RFD (0-400ms) ($N \cdot s^{-1}$), for both the eccentric and concentric phases. Mean bar velocity was chosen over peak bar velocity for a better representation of each athlete's ability to move load throughout the whole lifting phase (concentric/eccentric) (Jidovtseff, Harris, Crielaard, & Cronin, 2011). A separate single force platform (Model ACP, Advanced Mechanical Technology, Inc., Watertown, Massachusetts, USA) housed in a custom-built weightlifting platform was used to collect all kinetic snatch and clean data at a sampling rate of 1000Hz. Pilot determined both force plates to be reliable and accurate. Nine infra-red cameras (T10S, Vicon Motion System Ltd., Oxford, UK) were strategically placed around the force platforms in the collection. A total of eight reflective markers (10mm diameter) markers were placed in specific locations following previous research (McKenzie, Brughelli, Whatman, & Brown, 2015) on the centre of both ends of the barbell (2) and on the right side of the participants bodies (6) in the following anatomical locations: 1) acromion process, 2) greater trochanter, 3) lateral epicondyle of the femur, 4) lateral malleolus, 5) top of the heal lift of the lifting shoe and in-line with the lateral malleolus and, 6) base of the fifth metatarsal to create five rigid segments. The infra-red cameras were arranged so that each marker could be seen by a minimum of three cameras at any point and time, to allow for reconstruction of three-dimensional trajectories. The collection space was calibrated with an error of no greater than 0.2 (route mean squared in camera pixels; the difference between the 2D image of each marker on the camera sensor and the 3D reconstructions of those markers projected back to the cameras sensor) for each camera prior to each data collection session and a point of origin was positioned at the corner of one of the force platforms to establish a local relationship between the camera positions and the laboratory origin. Data from the retroreflective markers was used to analyse bar path and joint angles throughout the squat movement using Vicon Nexus software (Version 1.8.5, Vicon Motion System Ltd., Oxford, UK).

Data reduction

For the purpose of this study, the two embedded force platforms were combined and all data was filtered with a low-pass fourth-order zero-lag Butterworth filter using a cut-off frequency of 16 Hz in a custom-made LabVIEW programme (Version 14.0, National Instruments Corp., Austin, TX, USA) based on residual analysis and visual inspection of the kinematic and kinetic data. Kinematic variables of interest were gathered through an individual analysis within the start and finish of the squat, snatch and clean movements to calculate the range-of-motion (peak flexion – initial or finishing flexion) and peak flexion angles for the hip, knee and ankle joints (Figures 5, 6 and 7). The hip range-of-motion in the sagittal plane was derived from the anterior angle between the thorax (trunk) and the thigh, the knee range-of-motion was derived from the posterior angle between the thigh and the shank and the ankle range-of-motion was derived from the angle between the shank and the foot. In all cases, the actual angle is presented as opposed to the raw angle (see Figure 2). Kinetic variables of

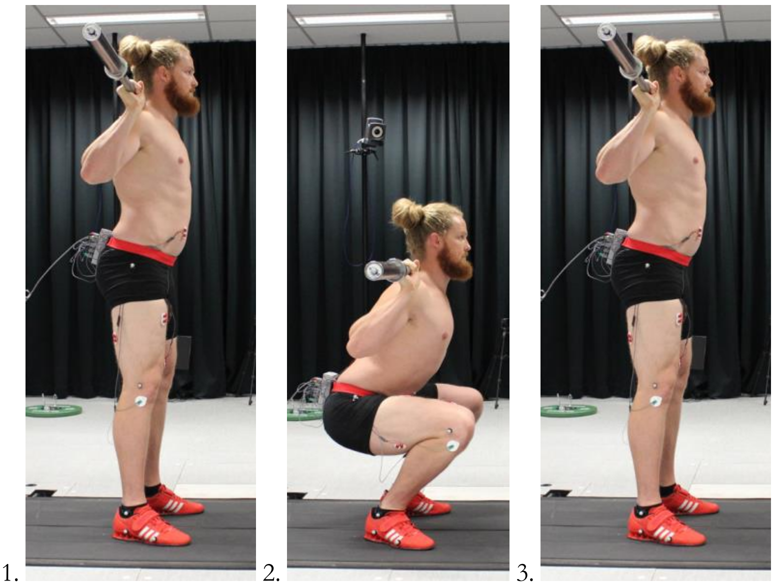


Figure 5: Joint angles of the HBBS at 1) the start position; 2) the hole: peak flexion; and 3) the finish position.

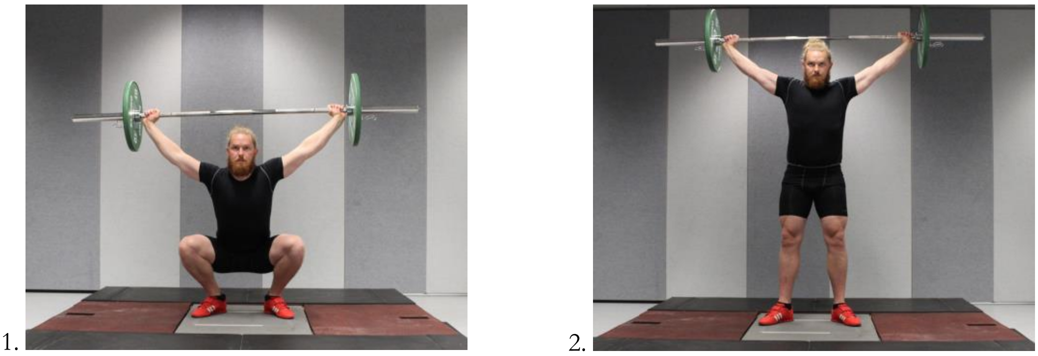


Figure 6: Joint angles of the snatch at 1) the catch: position peak flexion; and 2) the finish flexion.

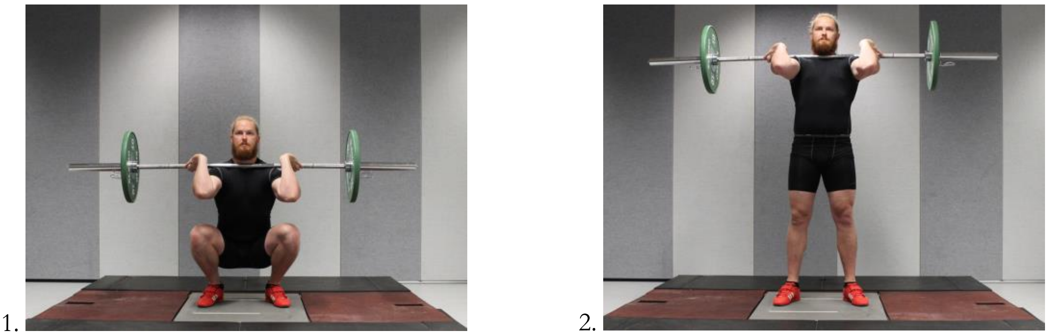


Figure 7: Joint angles of the clean at 1) the catch: position peak flexion; and 2) the finish flexion.

interest were obtained from an analysis of the eccentric phase (from the initiation of a negative [downward] velocity of the right-side bar marker to the instant the marker reached zero velocity [the hole]), and concentric phase (from the initiation of a positive [upward] velocity of the right-side bar marker to the instant the marker reached zero velocity a second time [the top]). The eccentric RFD is measured in the time before this change from the eccentric phase to the concentric phase. That is, 0-50ms is the final 50ms, and 0-400ms is the final 400ms prior to the start of the concentric phase. In the concentric phase, the 0-

50ms is the first 50ms of the ascent to full extension. Phase-linked kinetic data were then processed (Table 8).

Statistical analysis

Prior to analyses, data were split into four categories according to the %1RM load: (1) 74-83%, (2) 84-93%, (3) 94-99%, and (4) 100%. Generalised linear mixed models using a normal distribution with an identity link and unstructured covariance structure were used to estimate the difference in outcome variables between bar height across all four load groups while adjusting for the random effect of subject. Robust standard errors, constructed using the 'sandwich estimator' of the covariance structure, were used to control for possible misspecifications of the correlation structure. An alpha of 0.05 was used to determine significant associations. Multiple pairwise comparisons were corrected for inflation of Type 1 error using the Bonferroni method. Cohen's d statistic was calculated to provide additional information on the magnitude of the associations, with 0.2, 0.5, and 0.8 representing small, moderate, and large effects, respectively (Cohen, 1992). The analysis used IBM SPSS Statistics v. 23.0.0.0, IBM, Armonk, NY, USA) software.

Results

Load

The order of the lifts with regards to the greatest load lifted was shown to be HBBS, clean and then snatch (Tables 22, and 23). This is in line the participant's personal bests and predicted 1RM's. All loads, and loads relative to body weight produced significant differences ($p < 0.05$; or $p < 0.001$) between each lift type (i.e. HBBS vs snatch; HBBS vs clean; and snatch vs clean). Multiplication factors were derived from dividing the average loads of one lift by the average loads of another, to determine the relative difference between the two lifts in load. A comparison of loads, and the multiplication factors of load between each lift is presented in Table 24.

Centre of pressure

In the analysis of bar distance from the centre of pressure (COP), a negative number is indicative of the bar being positioned behind the COP. The distance of the bar to COP showed the HBBS, and snatch to have comparable distances behind the COP (Table 25).

Table 22: Mean loads lifted across all %1RM ranges.

% Range	Variable	HBBS	Snatch	Clean	HBBS vs Snatch Diff; ±90%CI	HBBS vs Clean Diff; ±90%CI	Snatch vs Clean Diff; ±90%CI
74-83%	Load (kg)	136.6 ± 23.5**§	76.8 ± 15.8**^	94.6 ± 14.2§^	60.2 ± 60.2	41.8 ± 41.8	18.2 ± 18.2
	*BW	1.6 ± 0.2**§§	0.9 ± 0.2**^^	1.1 ± 0.2§§^^	0.7 ± 0.7	0.5 ± 0.5	0.2 ± 0.2
84-93%	Load (kg)	152.5 ± 23.1*§	84.1 ± 14.1*^^	105.6 ± 14.6§^^	58.7 ± 58.7	50.7 ± 50.7	20.3 ± 20.3
	*BW	1.8 ± 0.2**§§	1.0 ± 0.1**^^	1.3 ± 0.2§§^^	0.8 ± 0.8	0.6 ± 0.6	0.3 ± 0.3
94-99%	Load (kg)	164.0 ± 24.7*§	90.6 ± 13.1^	113.4 ± 16.8§^	73.0 ± 73.0	46.9 ± 46.9	22.7 ± 7.2
	*BW	2.0 ± 0.2**§§	1.1 ± 0.1**^	1.4 ± 0.2§§^	1.0 ± 1.0	0.6 ± 0.6	0.3 ± 0.3
100%	Load (kg)	169.5 ± 26.5**§§	95.4 ± 13.6**^^	119.2 ± 17.0§§^^	72.9 ± 72.9	50.3 ± 50.3	22.7 ± 22.7
	*BW	1.9 ± 0.3**§§	1.2 ± 0.1**	1.4 ± 0.2§§	0.9 ± 0.9	0.6 ± 0.6	0.3 ± 0.3

HBBS, High-bar back-squat; BW, Body weight; CI, Confidence interval. All load data is presented as mean ± standard deviation.
* $p < 0.05$ HBBS to Snatch, ** $p < 0.001$ HBBS to Snatch; § $p < 0.05$ HBBS to Clean, §§ $p < 0.001$ HBBS to Clean; ^ $p < 0.05$ Snatch to Clean, ^^ $p < 0.001$ Snatch to Clean.

Table 23: Mean loads lifted effect sizes and percentage differences.

		HBBS vs Snatch		HBBS vs Clean		Snatch vs Clean	
% Range	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
74-83%	Load (kg)	2.0^	77.9	1.6^	44.4	1.5^	18.8
	*BW	2.8^	77.8	3.0^	45.5	1.9^	18.2
84-93%	Load (kg)	1.7^	81.3	1.8^	44.4	3.1^	20.4
	*BW	2.8^	80.0	3.1^	38.5	2.0^	23.1
94-99%	Load (kg)	1.4^	81.0	1.6^	44.6	0.2*	20.1
	*BW	2.6^	81.8	2.2^	42.9	1.2^	21.4
100%	Load (kg)	2.0^	77.7	2.2^	42.2	2.4^	20.0
	*BW	2.7^	58.3	3.9^	35.7	1.1^	14.3

HBBS, High-bar back-squat; BW, Body weight.
* = Small effect $d \geq 0.2$; ^ = Large effect $d \geq 0.8$.

Table 24: Load comparison multiplication factors.

% Range	HBBS/Snatch	Snatch/HBBS	HBBS/Clean	Clean/HBBS	Snatch/Clean	Clean/Snatch
74-83%	1.78	0.56	1.44	0.69	0.81	1.23
84-93%	1.81	0.55	1.44	0.69	0.80	1.26
94-99%	1.81	0.55	1.45	0.69	0.80	1.25
100%	1.78	0.56	1.42	0.70	0.80	1.25
Mean ± Standard Deviation	1.80 ± 0.02	0.56 ± 0.01	1.44 ± 0.01	0.69 ± 0.01	0.80 ± 0.1	1.25 ± 0.01

HBBS, High-bar back-squat.

Table 25: Distance of centre of pressure to bar results.

% Range	HBBS (mm)	Snatch (mm)	Clean (mm)
74-83%	-19 ± 42	-20 ± 52	4 ± 53
84-93%	-20 ± 40	-22 ± 67	-4 ± 59
94-99%	-23 ± 29	-44 ± 71	4 ± 30
100%	-24 ± 40	-17 ± 77	18 ± 35

HBBS, High-bar back-squat. Negative number represents the bar a distance behind the centre of pressure, positive number represents the bar a distance in front of the centre of pressure.
All centre of pressure data is presented as mean ± standard deviation.

Kinematics

The differences in kinematic joint angles are presented in Table 26. At 74-83% 1RM, the snatch displayed a significantly larger peak knee flexion angle, than the HBBS ($p < 0.05$; d = 0.8; % Diff = 19.7). However, the HBBS displayed a larger knee ROM than the snatch in the 74-83% 1RM range ($p < 0.05$; d = 1.3; % Diff = 33.8). Furthermore, at 74-83% 1RM, the clean displayed a significantly larger hip ROM than the snatch ($p < 0.05$; d = 0.9; % Diff = 17.9). No significant differences in kinematic results were observed between any of the three lift types at 84-93% and 94-99% 1RM. At 100% 1RM, the clean presented a significantly larger knee ROM that the HBBS ($p < 0.05$; d = 0.9; % Diff = 5.4). Furthermore, the majority of variables across all four percentages of 1RM displayed small ($d \geq 0.2$) moderate ($d \geq 0.5$) and large ($d \geq 0.8$) effect sizes (Table 27).

Kinetic

A greater number of significant differences were observed across the kinetic variables, and are presented in Tables 28 – 31. Noticeably, all variables show significance between at least one lift combination (i.e. HBBS vs snatch; HBBS vs clean; and snatch vs clean), except for the RFD 0-50ms and 0-400ms of the eccentric phase, and RFD 0-50ms of the concentric phase which showed no significant differences across any load ranges between any lift comparisons. Furthermore, the majority of variables across all four percentages of 1RM ranges displayed small ($d \geq 0.2$) moderate ($d \geq 0.5$) and large ($d \geq 0.8$) effect sizes (Tables 32 - 35).

Discussion

The purpose of this study was to compare and contrast the kinematic and kinetic differences between the HBBS, and the Olympic weightlifting snatch and clean. This assessment provides empirical data that can be used to evaluate the utility of the HBBS as a supplementary exercise for Olympic weightlifting. Furthermore, the relationship between the lifts (load multiplication factors) may be used in a predictive manner for Olympic weightlifting coaches to prescribe appropriate loads for one lift based on the performance of another.

To the best of our knowledge, this is the first study to compare the kinematic and kinetic differences of the HBBS, snatch and clean using loads ≥ 90%1RM. The main findings of this investigation were; 1) no significant kinematic differences were observed between any of the three lifts at 84-93% and 94-99% 1RM; however small to large effects (d = 0.2 – 0.8)

Table 26: Kinematic results

% 1RM Range	Joint	Variable	HBBS Angle (°)	Snatch Angle (°)	Clean Angle (°)	HBBS to Snatch Diff; ±90%CI	HBBS to Clean Diff; ±90%CI	Snatch to Clean Diff; ±90%CI
74-83%	Hip	Peak Flexion	69 ± 7	68 ± 22	59 ± 19	5 ± 13	13 ± 16	6 ± 8
		ROM	100 ± 8	90 ± 18^	110 ± 17^	10 ± 15	9 ± 14	20 ± 20
	Knee	Peak Flexion	54 ± 7*	68 ± 9*	70 ± 16	11 ± 11	15 ± 15	2 ± 14
		ROM	116 ± 7*	86 ± 33*	101 ± 19	33 ± 33	15 ± 16	21 ± 21
	Ankle	Peak Dorsiflexion	90 ± 5	92 ± 6	91 ± 5	0 ± 3	0 ± 3	0 ± 4
		ROM	33 ± 4	25 ± 16	33 ± 5	4 ± 11	1 ± 5	6 ± 6
84-93 %	Hip	Peak Flexion	69 ± 9	86 ± 43	78 ± 26	15 ± 34	6 ± 17	8 ± 37
		ROM	100 ± 9	81 ± 39	91 ± 25	20 ± 31	6 ± 18	11 ± 33
	Knee	Peak Flexion	56 ± 7	81 ± 34	60 ± 23	24 ± 33	3 ± 15	21 ± 39
		ROM	114 ± 7	87 ± 38	112 ± 19	28 ± 30	15 ± 16	25 ± 33
	Ankle	Peak Dorsiflexion	91 ± 4	92 ± 5	91 ± 4	1 ± 4	0 ± 4	0 ± 3
		ROM	33 ± 4	28 ± 14	33 ± 2	2 ± 4	0 ± 4	2 ± 3
94-99%	Hip	Peak Flexion	71 ± 10	85 ± 17	84 ± 23	10 ± 20	8 ± 22	2 ± 15
		ROM	98 ± 10	81 ± 17	83 ± 19	18 ± 20	12 ± 20	4 ± 15
	Knee	Peak Flexion	56 ± 7	63 ± 28	55 ± 21	7 ± 23	5 ± 17	8 ± 24
		ROM	113 ± 8	104 ± 24	116 ± 19	11 ± 21	6 ± 17	12 ± 21
	Ankle	Peak Dorsiflexion	90 ± 5	92 ± 7	91 ± 5	1 ± 6	4 ± 4	1 ± 4
		ROM	33 ± 4	29 ± 15	33 ± 2	1 ± 5	2 ± 3	2 ± 4
100%	Hip	Peak Flexion	71 ± 9	73 ± 8	76 ± 15	2 ± 8	5 ± 10	3 ± 8
		ROM	97 ± 10	92 ± 11	95 ± 13	5 ± 6	3 ± 8	2 ± 10
	Knee	Peak Flexion	56 ± 7	53 ± 15	52 ± 15	3 ± 9	4 ± 9	1 ± 10
		ROM	113 ± 9§	114 ± 10	119 ± 12§	2 ± 4	6 ± 6	5 ± 6
	Ankle	Peak Dorsiflexion	90 ± 5	91 ± 7	89 ± 6	1 ± 3	1 ± 3	1 ± 54
		ROM	32 ± 3	29 ± 14	36 ± 3	2 ± 2	3 ± 3	1 ± 1

HBBS, High-Bar Back-Squat; ROM, Range of motion; CI, Confidence interval. All kinematic data presented at mean ± standard deviation.
* $p < 0.05$ HBBS to Snatch; § $p < 0.05$ HBBS to Clean; ^ $p < 0.05$ Snatch to Clean.

Table 27: Kinematic effect sizes and percentage differences

			HBBS vs Snatch		HBBS vs Clean		Snatch vs Clean	
% Range	Joint	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
74-83%	Hip	Peak Flexion	0.3*	0.9	0.5§	17.4	0.4*	16.4
		ROM	0.4*	11.3	0.4*	8.6	0.9^	17.9
	Knee	Peak Flexion	0.8^	19.7	0.7§	22.9	0.1	3.9
		ROM	1.3^	33.8	0.6§	14.7	0.7§	14.3
	Ankle	Peak Dorsiflexion	0.1	1.4	0.0	1.2	0.0	0.2
		ROM	0.3*	29.3	0.1	1.7	0.6§	24.0
84-93%	Hip	Peak Flexion	0.3*	20.1	0.2*	11.8	0.1	10.4
		ROM	0.4*	24.0	0.2*	9.9	0.2*	11.4
	Knee	Peak Flexion	0.4*	30.7	0.1	6.7	0.3*	34.8
		ROM	0.6§	30.9	0.6§	1.4	0.5§	22.5
	Ankle	Peak Dorsiflexion	0.1	1.5	0.0	0.9	0.1	0.6
		ROM	0.3*	19.8	0.1	0.5	0.4*	16.9
94-99%	Hip	Peak Flexion	0.3*	16.7	0.2*	15.9	0.1	1.0
		ROM	0.5§	20.9	0.4*	17.5	0.2*	2.8
	Knee	Peak Flexion	0.2*	10.3	0.2*	2.1	0.2*	13.9
		ROM	0.3*	8.7	0.2*	2.8	0.3*	10.6
	Ankle	Peak Dorsiflexion	0.1	1.4	0.6§	1.0	0.1	0.4
		ROM	0.2*	11.3	0.3*	0.4	0.3*	9.8
100%	Hip	Peak Flexion	0.1	2.8	0.3*	6.2	0.2*	3.5
		ROM	0.6§	5.5	0.2*	2.9	0.1	2.5
	Knee	Peak Flexion	0.2*	5.1	0.3*	7.4	0.1	2.2
		ROM	0.2*	1.3	0.9^	5.4	0.5§	4.2
	Ankle	Peak Dorsiflexion	0.1	0.5	0.2*	1.1	0.0	1.7
		ROM	0.5§	11.1	0.7§	9.6	0.5§	18.6

HBBS, High-Bar Back-Squat; ROM, Range of motion.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 28: Kinetic results 74–83% 1RM

Phase	Variable	HBBS	Snatch	Clean	HBBS to Snatch Diff; ±90%CI	HBBS to Clean Diff; ±90%CI	Snatch to Clean Diff; ±90%CI
Eccentric	Mean Bar v (m.s^{-1})	0.51 ± 0.13*	0.28 ± 0.11*^^	0.69 ± 0.14^^	0.21 ± 0.21	0.17 ± 0.17	0.41 ± 0.41
	Peak F_v (N·kg^{-1})	37 ± 3**	25 ± 4**	30 ± 10	13 ± 13	7 ± 7	6 ± 7
	Impulse (N.kg^{-1}·s)	37 ± 7*§§	14 ± 12	12 ± 5§§	24 ± 24	24 ± 24	2 ± 9
	RFD (0-50ms) (N·s^{-1})	2746 ± 1080	2708 ± 2005	2940 ± 2387	190 ± 851	195 ± 1825	580 ± 2198
	RFD (0-100ms) (N·s^{-1})	3657 ± 1788*	1842 ± 1103*	2978 ± 1961	1891 ± 1891	789 ± 2065	1263 ± 1674
	RFD (0-200ms) (N·s^{-1})	3832 ± 1528*	1943 ± 1446*	3468 ± 2347	1955 ± 1955	493 ± 2131	1610 ± 2168
	RFD (0-300ms) (N·s^{-1})	3005 ± 973	2914 ± 2039	2821 ± 1403	112 ± 1789	265 ± 1306	103 ± 1467
	RFD (0-400ms) (N·s^{-1})	2379 ± 755	2315 ± 1488	1966 ± 845	88 ± 1314	435 ± 532	290 ± 1338
Concentric	Mean Bar v (m.s^{-1})	0.51 ± 0.05*§§	0.40 ± 0.08*^^	0.72 ± 0.08§§^^	0.11 ± 0.11	0.21 ± 0.21	0.32 ± 0.32
	Peak F_v (N·kg^{-1})	37 ± 3**	22 ± 3**^	31 ± 8^	15 ± 15	6 ± 6	9 ± 9
	Impulse (N.kg^{-1}·s)	35 ± 3*§	25 ± 13*	20 ± 7§	10 ± 10	15 ± 15	4 ± 6
	RFD (0-50ms) (N·s^{-1})	2013 ± 737	1967 ± 1236	2292 ± 1401	28 ± 1093	209 ± 1177	384 ± 1477
	RFD (0-100ms) (N·s^{-1})	3110 ± 1502	2223 ± 2057	2900 ± 1588	886 ± 1575	293 ± 1720	738 ± 2075
	RFD (0-200ms) (N·s^{-1})	4070 ± 1791*	1918 ± 1911*	3316 ± 1864	2142 ± 2142	911 ± 1866	1397 ± 2083
	RFD (0-300ms) (N·s^{-1})	3485 ± 1267*	1463 ± 1329*	2784 ± 1290	2008 ± 2008	821 ± 1339	1304 ± 1448
	RFD (0-400ms) (N·s^{-1})	2707 ± 865**	991 ± 766**^	2212 ± 684^	17141 ± 1714	536 ± 848	1235 ± 1235

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.
* $p < 0.05$ HBBS to Snatch, ** $p < 0.001$ HBBS to Snatch; § $p < 0.05$ HBBS to Clean, §§ $p < 0.001$ HBBS to Clean; ^ $p < 0.05$ Snatch to Clean, ^^ $p < 0.001$ Snatch to Clean.

Table 29: Kinetic results 84-93% 1RM

Phase	Variable	HBBS	Snatch	Clean	HBBS to Snatch Diff; ±90%CI	HBBS to Clean Diff; ±90%CI	Snatch to Clean Diff; ±90%CI
Eccentric	Mean Bar v (m.s^{-1})	0.48 ± 0.09**	0.25 ± 0.07**^	0.64 ± 0.30^	0.25 ± 0.25	0.12 ± 0.23	0.39 ± 0.39
	Peak F_v (N·kg^{-1})	410 ± 3**§	25 ± 5**	32 ± 10§	14 ± 14	9 ± 9	7 ± 7
	Impulse (N.kg^{-1}·s)	42 ± 7**§§	17 ± 6**^	12 ± 4§§^	25 ± 25	29 ± 29	6 ± 6
	RFD (0-50ms) (N·s^{-1})	2258 ± 943	2117 ± 1069	3393 ± 2195	353 ± 492	1123 ± 1911	1271 ± 1683
	RFD (0-100ms) (N·s^{-1})	3413 ± 1587§	2923 ± 1094	2111 ± 1518§	131 ± 1227	2627 ± 2627	836 ± 1321
	RFD (0-200ms) (N·s^{-1})	3934 ± 1476*	2130 ± 1207*	2962 ± 1957	1614 ± 1227	1393 ± 1868	837 ± 1767
	RFD (0-300ms) (N·s^{-1})	3204 ± 900	1992 ± 1056^	3197 ± 872^	1042 ± 1158	341 ± 1053	1194 ± 1194
	RFD (0-400ms) (N·s^{-1})	2525 ± 601	2303 ± 1751	2888 ± 375	203 ± 1454	193 ± 553	578 ± 1030
Concentric	Mean Bar v (m.s^{-1})	0.41 ± 0.06§§	0.42 ± 0.07^^	0.71 ± 0.09§§^^	0.01 ± 0.07	0.27 ± 0.27	0.29 ± 0.29
	Peak F_v (N·kg^{-1})	39 ± 4**§	25 ± 4**^	33 ± 9§^	14 ± 14	7 ± 7	8 ± 8
	Impulse (N.kg^{-1}·s)	48 ± 7*§	31 ± 7*^	22 ± 9§^	15 ± 15	23 ± 23	9 ± 9
	RFD (0-50ms) (N·s^{-1})	2278 ± 921	1895 ± 1406	3160 ± 2224	92 ± 765	788 ± 1892	1262 ± 1330
	RFD (0-100ms) (N·s^{-1})	3303 ± 1632	1994 ± 934	3234 ± 2169	1457 ± 5015	532 ± 1927	1232 ± 1480
	RFD (0-200ms) (N·s^{-1})	4255 ± 1608*	2079 ± 1196*	3641 ± 1878	2143 ± 2143	1097 ± 1519	156 ± 1723
	RFD (0-300ms) (N·s^{-1})	3715 ± 1018*	1551 ± 930*	3040 ± 1439	2176 ± 2176	802 ± 1033	1492 ± 1492
	RFD (0-400ms) (N·s^{-1})	2897 ± 631*	1160 ± 691*^	2606 ± 512^	1684 ± 1684	703 ± 703	1465 ± 1465

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.
* $p < 0.05$ HBBS to Snatch, ** $p < 0.001$ HBBS to Snatch; § $p < 0.05$ HBBS to Clean, §§ $p < 0.001$ HBBS to Clean; ^ $p < 0.05$ Snatch to Clean, ^^ $p < 0.001$ Snatch to Clean.

Table 30: Kinetic results 94-99% 1RM

Phase	Variable	HBBS	Snatch	Clean	HBBS to Snatch Diff; ±90%CI	HBBS to Clean Diff; ±90%CI	Snatch to Clean Diff; ±90%CI
Eccentric	Mean Bar *v* ($m.s^{-1}$)	0.47 ± 0.09*	0.32 ± 0.13*^	0.67 ± 0.22^	0.26 ± 0.26	0.07 ± 0.21	0.34 ± 0.34
	Peak F_v ($N{\cdot}kg^{-1}$)	41 ± 4*	27 ± 4*	33 ± 9	12 ± 12	8 ± 8	6 ± 6
	Impulse ($N.kg^{-1}{\cdot}s$)	44 ± 8*§§	15 ± 10*	12 ± 4§§	23 ± 23	28 ± 28	3 ± 7
	RFD (0-50ms) ($N{\cdot}s^{-1}$)	2018 ± 1110	3579 ± 1868	4893 ± 3706	673 ± 2157	1923 ± 3321	698 ± 2228
	RFD (0-100ms) ($N{\cdot}s^{-1}$)	2953 ± 1658	2127 ± 878	5159 ± 4281	1628 ± 2126	1353 ± 4287	2261 ± 2481
	RFD (0-200ms) ($N{\cdot}s^{-1}$)	3532 ± 1817	1847 ± 1214	3305 ± 2034	1426 ± 2598	797 ± 2683	1105 ± 1407
	RFD (0-300ms) ($N{\cdot}s^{-1}$)	3031 ± 1224	2573 ± 2219	4403 ± 3186	853 ± 2059	528 ± 3128	1326 ± 2142
	RFD (0-400ms) ($N{\cdot}s^{-1}$)	2455 ± 754	3129 ± 1431	4051 ± 1962	741 ± 1635	761 ± 1848	362 ± 504
Concentric	Mean Bar *v* ($m.s^{-1}$)	0.32 ± 0.03§§	0.41 ± 0.07^^	0.62 ± 0.10§§^^	0.06 ± 0.07	0.27 ± 0.27	0.21 ± 0.21
	Peak F_v ($N{\cdot}kg^{-1}$)	41 ± 5**	25 ± 4**^	33 ± 8^	14 ± 14	7 ± 8	8 ± 8.
	Impulse ($N.kg^{-1}{\cdot}s$)	62 ± 3**§§	34 ± 7**	28 ± 11§§	29 ± 29	37 ± 37	7 ± 7
	RFD (0-50ms) ($N{\cdot}s^{-1}$)	2083 ± 906	2987 ± 2171	3432 ± 2306	1809 ± 2036	2581 ± 2581	217 ± 2483
	RFD (0-100ms) ($N{\cdot}s^{-1}$)	3425 ± 1412*	2313 ± 541*	3062 ± 1684	2017 ± 2017	476 ± 2073	497 ± 1536
	RFD (0-200ms) ($N{\cdot}s^{-1}$)	4357 ± 1500	2163 ± 632	2940 ± 1660	2114 ± 2114	834 ± 1792	821 ± 1275
	RFD (0-300ms) ($N{\cdot}s^{-1}$)	3778 ± 1088	1700 ± 838	2674 ± 1246	1843 ± 1843	737 ± 1199	1042 ± 1042
	RFD (0-400ms) ($N{\cdot}s^{-1}$)	2905 ± 767	1292 ± 672	2356 ± 1193	1394 ± 1394	295 ± 1123	1465 ± 1465

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.

* $p < 0.05$ HBBS to Snatch, ** $p < 0.001$ HBBS to Snatch; §§ $p < 0.001$ HBBS to Clean; ^ $p < 0.05$ Snatch to Clean, ^^ $p < 0.001$ Snatch to Clean.

Table 31: Kinetic results 100% 1RM

Phase	Variable	HBBS	Snatch	Clean	HBBS to Snatch Diff; ±90%CI	HBBS to Clean Diff; ±90%CI	Snatch to Clean Diff; ±90%CI
Eccentric	Mean Bar v (m.s^{-1})	0.48 ± 0.09	0.40 ± 0.16	0.67 ± 0.27	0.08 ± 0.12	0.19 ± 0.21	0.27 ± 0.27
	Peak F_v (N·kg^{-1})	42 ± 4**	28 ± 5**	34 ± 10	13 ± 13	8 ± 8	6 ± 6
	Impulse (N.kg^{-1}·s)	44 ± 9**§§	15 ± 13**	16 ± 3§§	30 ± 30	29 ± 29	1 ± 10
	RFD (0-50ms) (N·s^{-1})	2240 ± 852	3337 ± 1335	4464 ± 4834	1097 ± 1172	224 ± 4128	1127 ± 3026
	RFD (0-100ms) (N·s^{-1})	3062 ± 1681	2485 ± 2064	4863 ± 4858	577 ± 1901	1801 ± 34230	2378 ± 3905
	RFD (0-200ms) (N·s^{-1})	3535 ± 1767	2237 ± 1286	3431 ± 3157	1298 ± 1572	104 ± 2180	1194 ± 2456
	RFD (0-300ms) (N·s^{-1})	2984 ± 1233	3089 ± 2002	3501 ± 4348	106 ± 1740	517 ± 3237	411 ± 2800
	RFD (0-400ms) (N·s^{-1})	2417 ± 823	3608 ± 2469	2793 ± 3125	1191 ± 1926	376 ± 2328	816 ± 2625
Concentric	Mean Bar v (m.s^{-1})	0.22 ± 0.03*§§	0.39 ± 0.09*	0.51 ± 0.10§§	0.17 ± 0.17	0.29 ± 0.29	0.12 ± 0.12
	Peak F_v (N·kg^{-1})	41 ± 4**	26 ± 4**^	33 ± 9^	15 ± 15	9 ± 130	7 ± 7
	Impulse (N.kg^{-1}·s)	96 ± 11**§§	39 ± 16**	34 ± 8§§	56 ± 56	62 ± 62	5 ± 12
	RFD (0-50ms) (N·s^{-1})	1734 ± 916	2772 ± 1451	3271 ± 4659	1038 ± 1270	1537 ± 4339	498 ± 3611
	RFD (0-100ms) (N·s^{-1})	3218 ± 1572	2793 ± 1826	2769 ± 2197	425 ± 1783	449 ± 1881	24 ± 1929
	RFD (0-200ms) (N·s^{-1})	4310 ± 1678*§	2047 ± 1380*	3039 ± 1519§	2263 ± 2263	1271 ± 1271	992 ± 1292
	RFD (0-300ms) (N·s^{-1})	3745 ± 1123*§	1587 ± 815*	2769 ± 1366§	2158 ± 2158	976 ± 976	1182 ± 1182
	RFD (0-400ms) (N·s^{-1})	2911 ± 729**	1238 ± 547**^	2342 ± 1276^	1673 ± 1673	569 ± 777	1104 ± 1104

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development; CI, Confidence interval. All kinetic data presented at mean ± standard deviation.
* $p < 0.05$ HBBS to Snatch, ** $p < 0.001$ HBBS to Snatch; § $p < 0.05$ HBBS to Clean, §§ $p < 0.001$ HBBS to Clean; ^ $p < 0.05$ Snatch to Clean.

Table 32: Kinetic effect sizes and percentage differences 74–83% 1RM

Phase	Variable	HBBS vs Snatch		HBBS vs Clean		Snatch vs Clean	
		Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v (m.s^{-1})	1.2^	80.5	0.7§	27.1	2.5^	59.6
	Peak F_v (N·kg^{-1})	3.9^	49.7	0.7§	23.6	0.5§	17.5
	Impulse (N.kg^{-1}·s)	1.3^	161.1	3.2^	211.9	0.1	19.4
	RFD (0-50ms) (N·s^{-1})	0.1	1.4	0.1	6.6	0.2*	7.9
	RFD (0-100ms) (N·s^{-1})	1.0^	98.5	0.2*	22.8	0.5§	38.1
	RFD (0-200ms) (N·s^{-1})	1.2^	97.2	0.1	10.5	0.5§	44.0
	RFD (0-300ms) (N·s^{-1})	0.0	3.1	0.1	6.5	0.0	3.3
	RFD (0-400ms) (N·s^{-1})	0.0	2.8	0.5§	21.0	0.1	17.7
Concentric	Mean Bar v (m.s^{-1})	0.8^	26.0	3.2^	29.6	2.3^	44.1
	Peak F_v (N·kg^{-1})	4.6^	65.5	0.7§	20.1	0.9^	27.4
	Impulse (N.kg^{-1}·s)	0.9^	38.7	1.5^	77.6	0.4*	28.1
	RFD (0-50ms) (N·s^{-1})	0.0	2.3	0.1	12.2	0.2*	14.2
	RFD (0-100ms) (N·s^{-1})	0.3*	64.5	0.1	26.1	0.2*	23.3
	RFD (0-200ms) (N·s^{-1})	1.1^	112.2	0.3*	22.7	0.4*	42.2
	RFD (0-300ms) (N·s^{-1})	1.4^	138.2	0.4*	25.2	0.5§	47.5
	RFD (0-400ms) (N·s^{-1})	1.9^	173.3	0.4*	22.4	0.9^	55.2

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 33: Kinetic effect sizes and percentage differences 84-93% 1RM

		HBBS vs Snatch		HBBS vs Clean		Snatch vs Clean	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v (m.s^{-1})	1.8^	93.7	0.3*	25.6	1.2^	61.6
	Peak F_v (N·kg^{-1})	2.6^	61.1	0.8^	26.1	0.7§	21.7
	Impulse (N.kg^{-1}·s)	2.1^	142.6	3.1^	259.9	0.9^	48.3
	RFD (0-50ms) (N·s^{-1})	0.4*	6.7	0.4*	33.4	0.5§	37.6
	RFD (0-100ms) (N·s^{-1})	0.1	16.8	0.9^	61.7	0.4*	38.5
	RFD (0-200ms) (N·s^{-1})	0.8^	84.7	0.5§	32.8	0.3*	28.1
	RFD (0-300ms) (N·s^{-1})	0.5	60.8	0.2*	0.2	1.0^	37.7
	RFD (0-400ms) (N·s^{-1})	0.1	9.7	0.2*	12.5	0.3*	20.3
Concentric	Mean Bar v (m.s^{-1})	0.1	1.9	2.4^	41.5	2.3^	40.4
	Peak F_v (N·kg^{-1})	4.6^	59.2	0.9^	19.6	0.9^	24.9
	Impulse (N.kg^{-1}·s)	1.2^	55.3	1.7^	115.9	0.9^	39.1
	RFD (0-50ms) (N·s^{-1})	0.1	20.2	0.3*	27.9	0.6§	40.0
	RFD (0-100ms) (N·s^{-1})	0.2*	71.2	0.2*	5.5	0.5§	38.4
	RFD (0-200ms) (N·s^{-1})	0.8^	104.6	0.4*	16.9	0.6§	42.9
	RFD (0-300ms) (N·s^{-1})	1.1^	139.5	0.5§	22.2	0.7^	49.0
	RFD (0-400ms) (N·s^{-1})	1.1^	149.8	0.6§	11.1	1.1^	55.5

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 34: Kinetic effect sizes and percentage differences 94–99% 1RM

		HBBS vs Snatch		HBBS vs Clean		Snatch vs Clean	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar *v* ($m.s^{-1}$)	1.8^	45.1	0.3*	30.5	1.2^	52.1
	Peak F_v ($N \cdot kg^{-1}$)	2.6^	52.5	0.8^	22.7	0.7§	19.5
	Impulse ($N.kg^{-1} \cdot s$)	2.1^	185.7	3.1^	254.3	0.9^	24.0
	RFD (0-50ms) ($N \cdot s^{-1}$)	0.4*	43.6	0.4*	58.8	0.5§	26.8
	RFD (0-100ms) ($N \cdot s^{-1}$)	0.1	38.8	0.9^	42.8	0.4*	58.8
	RFD (0-200ms) ($N \cdot s^{-1}$)	0.8^	91.2	0.5§	6.8	0.3*	44.1
	RFD (0-300ms) ($N \cdot s^{-1}$)	0.5§	17.8	0.2*	31.2	1.0^	41.6
	RFD (0-400ms) ($N \cdot s^{-1}$)	0.1	21.6	0.2*	39.4	0.3*	22.8
Concentric	Mean Bar *v* ($m.s^{-1}$)	0.1	21.1	2.4^	47.6	2.3^	33.5
	Peak F_v ($N \cdot kg^{-1}$)	4.6^	63.5	0.9^	23.4	0.9^	24.5
	Impulse ($N.kg^{-1} \cdot s$)	1.2^	81.9	1.7^	125.7	0.9^	24.1
	RFD (0-50ms) ($N \cdot s^{-1}$)	0.1	30.3	0.3*	39.3	0.6§	13.0
	RFD (0-100ms) ($N \cdot s^{-1}$)	0.2*	27.6	0.2*	3.6	0.5§	24.4
	RFD (0-200ms) ($N \cdot s^{-1}$)	0.8^	101.5	0.4*	48.2	0.6§	26.4
	RFD (0-300ms) ($N \cdot s^{-1}$)	1.1^	122.3	0.5§	41.3	0.7§	36.4
	RFD (0-400ms) ($N \cdot s^{-1}$)	1.4^	124.9	0.6§	23.3	1.1^	45.2

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

Table 35: Kinetic effect sizes and percentage differences 100% 1RM

		HBBS vs Snatch		HBBS vs Clean		Snatch vs Clean	
Phase	Variable	Effect Size	% Difference	Effect Size	% Difference	Effect Size	% Difference
Eccentric	Mean Bar v (m.s^{-1})	0.4*	19.4	0.5§	28.5	0.7§	40.2
	Peak F_v (N·kg^{-1})	2.2^	46.3	0.7§	22.9	0.6§	16.0
	Impulse (N.kg^{-1}·s)	2.9^	199.9	2.4^	179.7	0.1	6.7
	RFD (0-50ms) (N·s^{-1})	0.6§	32.9	0.0	49.8	0.2*	25.3
	RFD (0-100ms) (N·s^{-1})	0.2*	23.2	0.3*	37.0	0.4*	48.9
	RFD (0-200ms) (N·s^{-1})	0.5§	58.0	0.0	3.0	0.3*	34.8
	RFD (0-300ms) (N·s^{-1})	0.0	3.4	0.1	14.8	0.1	11.8
	RFD (0-400ms) (N·s^{-1})	0.4*	33.0	0.1	13.5	0.2*	29.2
Concentric	Mean Bar v (m.s^{-1})	1.5^	44.0	3.2^	57.1	0.7§	23.4
	Peak F_v (N·kg^{-1})	3.1^	58.2	0.0	25.3	0.8^	20.8
	Impulse (N.kg^{-1}·s)	2.6^	144.0	4.2^	182.4	0.3*	15.7
	RFD (0-50ms) (N·s^{-1})	0.5§	37.4	0.2*	47.0	0.1	15.2
	RFD (0-100ms) (N·s^{-1})	0.1	9.6	0.1	10.6	0.0	0.9
	RFD (0-200ms) (N·s^{-1})	0.9^	110.5	0.8^	41.8	0.5§	32.6
	RFD (0-300ms) (N·s^{-1})	1.4^	135.9	1.1^	35.2	0.7§	42.7
	RFD (0-400ms) (N·s^{-1})	1.8^	135.1	0.4*	24.3	0.8^	47.1

HBBS, High-Bar Back-Squat; F_v, Vertical force; RFD, Rate of force development.
* = Small effect d ≥ 0.2; § = Moderate effect d ≥ 0.5; ^ = Large effect d ≥ 0.8.

among the hip and knee angles indicate notable differences between the three lifts in these ranges; 2) significant kinematic differences were observed between the HBBS and snatch in knee flexion and ROM at 74-83% 1RM ($d = 0.8$ and 1.3, respectively); between the HBBS and clean in knee ROM at 100% 1RM ($d = 0.9$); and between the snatch and clean in hip ROM at 74-83% 1RM ($d = 0.9$). A range of small to large effect sizes ($d = 0.2 – 0.8$) also indicated considerable differences between lift types in non-significant variables in these ranges; 3) a greater number of significant differences were observed in kinetic variables between each of the three lift combinations (i.e. HBBS vs snatch; HBBS vs clean; and snatch vs clean). However, the HBBS when compared to the snatch resulted in the greatest number of significant kinetic differences.

The kinematic joint angle results of this study indicate similarities between the HBBS and the snatch and clean, with a relatively small number of significant differences observed across the four ranges of 1RM load. At 74-83% 1RM, the snatch displayed a significantly larger peak knee flexion angle, than the HBBS ($p < 0.05$; $d = 0.8$; % Diff = 19.7). However, the HBBS displayed a larger knee ROM than the snatch in the 74-83% 1RM range ($p < 0.05$; $d = 1.3$; % Diff = 33.8). The greater ROM in the HBBS can be attributed to a difference in start/finish angle to the snatch, and the significantly greater depth that was attained during this movement. The significantly larger snatch peak knee flexion results of the present study are unexpected and conflict with prior research by Campos, Poletaev, Cuesta, Pablos, & Carratalá (2006) and Gourgoulis et al., (2002) who demonstrated the snatch to have a typically lower catch position (smaller angle) than the depth reached by the HBBS at maximum effort. The only significant difference between the HBBS and clean was a larger clean knee ROM at 100% of 1RM ($p < 0.05$; $d = 0.9$; %Diff = 5.4). This indicates that the HBBS has kinematic similarity to the clean. A significant difference in knee ROM without an accompanying significant difference in knee peak flexion angle, is indicative of a difference in peak extension (ROM = peak flexion – peak extension). Therefore, the results of this study show that at 100% of 1RM, the clean displays a greater knee angle at the start/finish position than the HBBS. This may be attributed to the larger loads in the HBBS, reducing the participant's ability to extend the knee joint to the extent that is possible with a lighter load, such as in the clean.

Furthermore, despite the obvious technique differences between the snatch and clean (i.e. overhead versus anterior shoulder bar positon), this study showed kinematic similarities between the two lifts. Only one significant difference was observed: a larger hip ROM at 74-

83% 1RM by the clean. Although not statistically significant, this trend also continues in average hip ROM in the following ranges of load (i.e. 84-93%, 94-99% and 100% 1RM) with small to moderate effects observed up until 100% 1RM ($d \geq 0.2 - 0.5$). As with the HBBS and clean, these results, coupled with a lack of significant differences in peak hip flexion indicate that the bar positional differences between the snatch and clean have an influence on the peak extension. For example, the overhead bar position in the snatch will push the torso into greater forward lean at the finish, in comparison to a more upright torso position in the clean. In addition, it should also be noted that differences in technique were displayed by each participant for each lift type, such as the position of the bar on the shoulders at the catch, and elbow height throughout the lift. These technique differences will have an influence on the final average angle, and the range of differences is indicated by the standard deviations presented.

The lack of significant differences in joint angles across all three joints, provides evidence to support the use of the HBBS as a supplementary exercise to the snatch and clean. In addition, due to the similarities in joint angles between the three lifts, these results indicate that the HBBS, snatch and clean may place comparable emphasis on the same muscle groups during the various phases of each lift. Future studies should seek to analyse the muscle activity of each lift, to confirm any similarities and explore any differences.

With regards to the bar distance from the COP, the results of this study demonstrated that on average, each of the three lifts were performed with a bar position close to the COP (≤ 43.72mm) which indicates a more upright body position, in comparison to a greater distance from the COP. However, it should be noted however that the large standard deviations for the COP indicate notable variations between participants (Table 25). The positions in which the bar is caught or placed at the measured position, can differ greatly from participant to participant. Such differences in catch position may be explained by a number of factors, including, experience, training age, different coaches, and training philosophies. In addition, the type of lift will also influence the bar position relative to the COP. For example, the results of the clean are generally positive, indicating a bar position in front of the COP. This is expected from the clean, as the movement is defined by a bar position anterior to the shoulder.

The results of this study indicate a greater number of significant kinetic differences than kinematic differences between the three lift combinations (i.e. HBBS vs snatch; HBBS vs clean; and snatch vs clean). The HBBS when compared to the snatch resulted in the greatest number of significant kinetic differences, and this is not surprising considering the overhead bar position in the snatch, in comparison to the anterior and posterior placement on the shoulders in the clean and HBBS, respectively. In the eccentric phase, the RFD 0-50ms; and RFD 0-400ms; and in the concentric phase the RFD 0-50ms, showed no significant differences between any of the three lift combinations at any range of load (%1RM). However, significant differences were observed between 400ms and 50ms (at 300ms, 200ms, and 100ms), and this can be attributed to the differences in technique between the three movements, as force is applied at different stages of the descent to bring the body to a point of zero velocity. The application of braking forces large enough to bring the body to a velocity of zero can be attributed to the intrinsic contractile properties of skeletal muscle (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). In order to generate the larger braking forces needed to slow heavier loads to a velocity of zero in the snatch and clean, improvements must be made to the contractile properties of the active muscles. The HBBS is an effective method to create improvements in the strength of skeletal muscle in the lower limb and torso (Cormie, McGuigan, & Newton, 2010a, 2010b; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004), and therefore acts as a supplementary exercise to the snatch and clean by increasing the ability of the active muscles to brake heavier loads in the snatch and clean. No significant RFD differences were observed at 0-50ms in the concentric phase between any of the three lift combinations at any range of load (%1RM). The force produced to initiate the concentric phase, can be attributed to the response of the stretch shortening cycle (SSC) and associated elastic energy build up from the eccentric phase being released (van Ingen Schenau, Bobbert, & de Haan, 2010). These results suggest that performing the HBBS, will result in an improvement in the SSC which can be applied to the snatch and clean. There is also an elastic effect cause though deformation of the barbell, anecdotally known as 'bar whip' (Chiu, Schilling, Fry, & Salem, 2008), present in the initial 0-50ms of the concentric phase. After the first 50ms of the concentric phase, differences in the techniques and relative loads of each movement then begin to influence the levels of force that must be produced to complete the repetition.

In both the eccentric and concentric phases, significantly larger F_v and impulse values were displayed by the HBBS when compared to the snatch. This was expected, due to the significantly larger loads lifted at each percentage of 1RM in the HBBS. Prior research has shown that as load is increased, there is a resulting increase in the F_v produced that is proportionate to the increase in load (Ebben & Jensen, 2002; Ebben et al., 2012; Flanagan

& Salem, 2007; Kellis, Arambatzi, & Papadopoulos, 2005; Zink, Perry, Robertson, Roach, & Signorile, 2006). The forces that are required to be produced in the HBBS in order to lift heavy loads will result in adaptations to the contractile components of skeletal muscle (Cormie, McGuigan, & Newton, 2010a, 2010b; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004). Despite the kinematic similarities between the HBBS, snatch and clean, the degree to which HBBS-induced increases in muscular strength and power transfer over to the snatch and clean has yet to be fully explored in a quantitative fashion. Thus, further analysis into muscle activity is warranted to understand the extent of strength and power transfer between the three lifts.

The potential ability to predict the performance of any of the three lifts analysed, by the performance of another was also explored in this study to add to the practical nature of Olympic weightlifting as a sport. The results showed, that within the highly trained participants of this study, there is the potential ability for HBBS performance to predict the load lifted for the snatch and clean. This is exemplified by a comparison of the average loads for each lift at each percentage of 1RM. Each average was divided by the other to create a multiplication factor (Table 25). Across all four ranges of load, the factor at which a load for one lift is to be multiplied by to predict the expected load for another lift (e.g. HBBS load x 0.56 = Snatch load) is consistent across all ranges within a standard deviation of $\leq$ 0.02. However, the authors recommend caution when attempting to predict performance via the use of this equation. In comparison to the HBBS, the snatch and clean are highly technical lifts that require considerable training in order to be performed correctly. Therefore, it is not recommended to predict performance in the snatch and clean based on the HBBS in novice trained lifters. Instead, it is recommended to apply such an equation within experienced Olympic weightlifters who demonstrate a sound degree of technical mastery. Future research, should expand on the multiplication factors equation with a larger cohort, in order to create a reliable equation for predicting performance in experienced lifters, and also look into the creation of an equation for recreationally trained athletes.

Limitations

Several limitations exist in the study, including the low number of participants (n = 6) as well as the lack of gender diversity of the participants. In addition, each participant was included in the study, on the provision that they were at or of national championship qualification level. However, there was individual differences in training experience (3.75 ± 2.72 years) which may have influenced the range of technical proficiency in the cohort. Similarly, not all lifters belonged to the same club which may have resulted in potential variation in lifting technique due to the influence of different coaches. All participants were recruited in a "strength phase" of their respective competition cycle. However, as a result the maximum loads lifted in testing may have been slightly under competition maximums, due to the fact that the participants were not in a competition peaking phase. Furthermore, the loads lifted in testing may not have been a fair representation of each participant's maximal clean, as the participants performed maximal clean and jerk lifts in testing, however only the clean part of the lift was analysed. Lastly, although efforts were made to ensure the testing closely replicated a typical Olympic weightlifting performance, there was inherent differences present (e.g. markers placed on the body and the elimination of support aids such as knee sleeves). These small differences may have caused the participants to subconsciously change their technique slightly. Further analysis into muscle activity is warranted to understand the extent of the similarities between the three lifts.

Practical applications

This study has provided evidence to support the use of the HBBS by Olympic weightlifters in training to supplement the competition lifts; the snatch and clean. The HBBS was also shown to replicate similar kinetic values to the snatch and clean in RFD. However, it is apparent that the differences in technique have a markedly larger influence on the kinetics of the three lifts in comparison to the kinematics. This study has shown that HBBS performance can predict snatch and clean performance, using the multiplication factors outlined. However, this equation should be reserved for use with experienced Olympic weightlifters who demonstrate a sound degree of technical mastery.

CHAPTER FIVE - Summary, practical applications and future research

Preface

The purpose of this chapter is to synthesise the literature review and experimental studies into meaningful information. Following a synthesis of results, practical applications will be provided that are pertinent to strength and conditioning practice and can directly affect Olympic weightlifters, powerlifters and recreationally trained lifters. Future recommendations and research direction will also be provided to guide researchers in the strength and conditioning field towards answering important questions pertaining to the back-squat and Olympic lifts.

Summary
This Master's thesis (1) reviewed the current literature and quantitatively assessed the kinetic and kinematic findings among the limited research; (2) compared and contrasted the high-bar back-squat and low-bar back-squat up to maximal effort; and (3) assessed the differences and similarities between the high-bar back-squat and the Olympic lifts.

A relatively small amount of research (Benz, 1989; Fry, Aro, Bauer, & Kraemer, 1993; Goodin, 2015; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; Wretenberg, Feng, & Arborelius, 1996) has been conducted on why the LBBS might allow heavier loads to be lifted compared to the HBBS, although no comparisons have been made between the HBBS and the Olympic lifts (i.e. snatch and clean and jerk). When reviewing the literature, the HBBS was found to commonly present a larger hip angle, smaller knee angle and equivalent ankle angle compared to the low-bar back-squat. These kinematic findings suggested that the HBBS creates a more upright truck position for the lifter thus potentially requiring more quadriceps muscle activation during the lift. In contrast, the LBBS was found to present a smaller hip angle suggesting more trunk lean but potentially more posterior-chain muscle activation. These findings helped establish the kinetic and kinematic norms that would we would expect to see in our subsequent experimental studies and provided insight into which variables would aid in answering the questions of the thesis.

The largest element missing in the back-squat literature was that no research had assessed the HBBS or LBBS greater that 90% 1RM. As such, the purpose of the first experimental study in this thesis was to compare and contrast the HBBS and LBBS up to maximal effort. A cross-sectional design was employed to quantify the joint kinematic and kinetic differences between the HBBS in OLY vs. the LBBS in POW, and the HBBS in control (HBCON) vs. the LBBS in control (LBCON). Small to moderate effects (d = 0.2-0.7) were observed between the OLY and POW for the hip and knee joints at each percentage of 1RM range; in line with the findings of previous research. These results support the findings of Benz (1989), Fry, Aro, Bauer, and Kraemer (1993) and Wretenberg, Feng, and Arborelius (1996) and indicate that the LBBS (POW) can be characterised by a smaller hip angle. This manifests as greater forward lean which is the body's postural control mechanism in response to the low-bar position, in order to resist perturbation and to maintain balance (Winter, 1995). Conversely, the HBBS (OLY) is shown to have a larger hip angle, which manifests as a more upright torso position which is anecdotally similar to the catch position in the snatch and clean (Wretenberg, Feng, & Arborelius, 1996). Additionally, the knee angle of the POW was

shown to be greater than the OLY, by small effect sizes (d = 0.2-0.4) which indicates that the HBBS results in a deeper squat (Escamilla et al., 2001; Flanagan & Salem, 2007; Han, Ge, Liu, & Liu, 2013; Hooper et al., 2014; Kobayashi et al., 2010; Miyamoto, Iinuma, Maeda, Wada, & Shimizu, 1999). The combination of forward lean at the hip, and greater knee angle in the LBBS results in a more pronounced use of the strong posterior hip musculature when compared to the HBBS which places greater emphasis on the knee musculature. This may be a leading reason why the LBBS allows for greater loads to be lifted. However, further research into the muscle activity patterns of each squat variation is warranted to confirm such a claim. In addition, an increase in stability, and decrease in hip moment arm length through these joint angles will contribute to a greater load lifted by the LBBS (Sato, Fortenbaugh, & Hydock, 2012; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012).

Larger loads were lifted by the POW than OLY on average (d = 0.2-0.3), as was expected. There were also moderate effects (d ≥ 0.05) showing the HBBS to produce larger RFD in each range of 1RM, except for 100% 1RM. Interestingly, significant differences were observed between the same bar positions in the experienced OLY and POW, and the resistance trained HBCON and LBCON group (i.e. OLY vs HBCON, and POW vs LBCON) in both kinematics and kinetics. This indicated that experience had a direct effect on the results of this study. Furthermore, the LBCON was shown to lift greater loads than the HBCON (d = 0.3-0.6), providing further evidence to support the use of the LBBS for lifting larger loads.

The second element missing in the back-squat literature was that no research had compared the HBBS to the Olympic lifts (snatch and clean and jerk). As such, the purpose of the second experimental study in this thesis was to assess the differences and similarities between the HBBS and the Olympic lifts. The same kinetic and kinematic variables from the first experimental study were used in this cross-sectional design to create a full profile of each of the three lifts (HBBS, snatch and clean). Small to large effects (d = 0.2–0.8) were observed across the four load ranges in all three joints between the HBBS and snatch and clean, which indicated that differences were present between the three lift types. However, these results did not reach statistical significance and can be explained by the technical differences between the three lifts. The distinctive upright torso, and smaller peak knee flexion angle of the HBBS is replicated by the snatch and clean in this study. These similarities observed, indicate that each lift is potentially utilising a similar lower body muscle recruitment strategy to complete each lift following peak flexion. The HBBS is supported as a supplementary exercise to the snatch and clean. Kinetic differences (d = 0.2–0.8) were observed in all variables in each of the four percentage of 1RM ranges. These differences can be explained by the larger loads lifted in the HBBS, and through the technical differences in performing each of the three lifts.

Practical applications

Participants performing the LBBS (i.e. POW and LBCON groups) were shown to lift heavier loads compared to participants performing the HBBS (i.e. OLY and HBCON groups). As a result, this thesis has provided evidence to support the use of the LBBS, when the goal is to lift the heaviest load possible. This is particularly applicable to powerlifters, where the back-squat is one of three completion lifts, and where the goal is to lift the heaviest possible load within the rules of the sport. Due to the technical differences in each back-squat style, practitioners seeking to develop the posterior hip muscular (i.e. gluteal, hamstring and spinal erector muscle groups) in a greater capacity than the anterior knee musculature (i.e. quadriceps), are advised to implement the LBBS. Furthermore, the HBBS appears more suited to those athletes who are required to strengthen and replicate movements that exhibit a more upright torso compared to the LBBS. This is exemplified by small to moderate effects between the OLY and POW (d = 0.2-0.7), and moderate to large effects between the HBCON and LBCON (d = 0.7-2.3), showing greater peak hip flexion in the HBBS of OLY and HBCON, in comparison to the LBBS of POW and LBCON. Similarities between the HBBS, and snatch and clean, in kinematic joint angles may indicate similar mechanics and that the same muscles may be active throughout each movement. Large differences, were shown between experienced high-bar and low-bar squatters, when compared to recreationally trained athletes. Therefore, it is recommended that experience level be accounted for, and distributed evenly between groups when seeking to analyse the effects of bar position on kinematic and kinetics. An equation was developed to allow for the ability to predict the performance (load) of the snatch and clean by the performance of the HBBS. Multiplication factors can be applied to experienced Olympic weightlifters' HBBS performance. However, the multiplication factors are not recommended to be used to predict snatch and clean performance from the HBBS performance in recreationally trained athletes due to the technical proficiency required to perform the snatch and clean.

Future research

In this thesis, muscle activity data were collected on eight key muscles surrounding (superior and inferior) the knee and hip; 1) the gastrocnemius medial head; 2) biceps femoris; 3) gluteus maximus; 4) erector spinae longissimus; 5) vastus medalis; 6) adductor magnus; 7) rectus femoris; and 8) rectus abdominis, in both experimental studies and for all lifts. However, this data was not presented due to the restrictions of time, and Master's thesis size limits. The use of this data for future research will be valuable to provide an insight into the muscles most active throughout the movements, which will allow for more accurate conclusions to be made as to why the LBBS enabled greater loads to be lifted. Muscle activity analysis between the HBBS and snatch and clean and jerk will also further strengthen the understanding of the similarities of the HBBS with the snatch and clean. Furthermore, the use of two embedded force platforms to collect squat kinetic data allows for the ability to split the kinetic data of this thesis into the forces applied through each leg. This division of the legs will allow for further research into asymmetries which will add to the body of current research. Lastly, future researchers should look to include larger athlete numbers to improve the statistical power of the studies along with including other athletic groups, such as female athletes. A greater number of athletes would also allow for the calculation of more accurate multiplication factors which would enable more reliable predications of HBBS, snatch and clean performances.

REFERENCES

Aagaard, P., Simonsen, E., Andersen, J., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology, 93*(4), 1318-1326. doi:10.1152/japplphysiol.00283.2002

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, K., & Behm, D. G. (2005). Trunk muscle activity increases with unstable squat movements. *Canadian Journal of Applied Physiology, 30*(1), 33-45.

Anderson, R., Courtney, C., & Casmeli, E. (1998). Emg analysis of the vastus medialis/vastus lateralis muscles utilizing the unloaded narrow-and wide-stance squats. *Journal of Sport Rehabilitation, 7*, 236-247.

Aurslanian, D. B. (1993). *Asymmetric lifting using a weight belt* (Master's thesis). Available from SPORTDiscus database. (SPH367417)

Bauer, J. A., Fry, A., & Carter, C. (1999). The use of lumbar-supporting weight belts while performing squats: erector spinae electromyographic activity. *Journal of Strength and Conditioning Research, 13*(4), 384-388.

Benda, B. J., Riley, P. O., & Krebs, D. E. (1994). Biomechanical relationship between center of gravity and center of pressure during standing. *Rehabilitation Engineering, 2*(1), 3-10.

Bentley, J. R., Amonette, W. E., De Witt, J. K., & Hagan, R. D. (2010). Effects of different lifting cadences on ground reaction forces during the squat exercise. *Journal of Strength and Conditioning Research, 24*(5), 1414-1420.

Benz, R. C. (1989). *A kinematic analysis of the high and low bar squat techniques by experienced low bar weight lifters* (Masters Thesis). West Chester University, Pennsylvania.

Bobbert, M. F., & Schamhardt, H. C. (1990). Accuracy of determining the point of force application with piezoelectric force plates. *Journal of Biomechanics, 23*(7), 705-710.

Bourne, N. D., & Reilly, T. (1991). Effect of a weightlifting belt on spinal shrinkage. *British Journal of Sports Medicine, 25*(4), 209-212.

Bressel, E., Willardson, J. M., Thompson, B., & Fontana, F. E. (2009). Effect of instruction, surface stability, and load intensity on trunk muscle activity. *Journal of Electromyography and Kinesiology, 19*(6), e500-e504.

Campos, J., Poletaev, P., Cuesta, A., Pablos, C., & Carratalá, V. (2006). Kinematical analysis of the snatch in elite male junior weightlifters of different weight categories. *Journal of Strength and Conditioning Research, 20*(4), 843-850.

Caterisano, A., Moss, R. E., Pellinger, 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.

Chandler, T. J., & Stone, M. H. (1992). The squat exercise in athletic conditioning: A position statement and review of the literature. *Chiropractic Sports Medicine, 6*, 105-105.

Chiu, L. Z. (2009). Sitting back in the squat. *Strength and Conditioning Journal, 31*(6), 25-27.

Chiu, L. Z., Schilling, B. K., Fry, A. C., & Salem, G. J. (2008). The influence of deformation on barbell mechanics during the clean pull. *Sports Biomechanics, 7*(2), 260-273.

Cohen, J. (1992). Statistical power analysis. *Current Directions in Psychological Science, 1*(3), 98-101.

Comfort, P., Stewart, A., Bloom, L., & Clarkson, B. (2014). Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *Journal of Strength and Conditioning Research, 28*(1), 173-177.

Cormie, P., McCaulley, G. O., & McBride, J. M. (2007). Power versus strength-power jump squat training: Influence on the load-power relationship. *Medicine and Science in Sports and Exercise, 39*(6), 996-1003.

Cormie, P., McCaulley, G. O., Triplett, N. T., & McBride, J. M. (2007). Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports and Exercise, 39*(2), 340-349.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise, 42*(8), 1582-1598.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine and Science in Sports and Exercise, 42*(8), 1566-1581.

DeForest, B. A., Cantrell, G. S., & Schilling, B. K. (2014). Muscle activity in single- vs. double-leg squats. *International Journal of Exercise Science, 7*(4), 302-310.

Delavier, F. (2010). *Strength training anatomy*. Champaign, IL: Human Kinetics.

Dintiman, G. B., & Ward, R. D. (2003). *Sports speed*. Champaign, IL: Human Kinetics.

Donnelly, D. V., Berg, W. P., & Fiske, D. M. (2006). The effect of the direction of gaze on the kinematics of the squat exercise. *Journal of Strength and Conditioning Research, 20*(1), 145-150. doi:10.1519/00124278-200602000-00023

Ebben, W. E., & 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., Garceau, L. R., Wurm, B. J., Suchomel, T. J., Duran, K., & Petushek, E. J. (2012). The optimal back squat load for potential osteogenesis. *Journal of Strength and Conditioning Research, 26*(5), 1232-1237. doi:10.1519/JSC.0b013e3182305321

Enoka, R. M. (1988). Muscle strength and its development. New perspectives. *Sports Medicine, 6*(3), 146-168.

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 Iii, C. T. (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.

Faber, G. S., Kingma, I., & van Dieën, J. H. (2010). Bottom-up estimation of joint moments during manual lifting using orientation sensors instead of position sensors. *Journal of Biomechanics, 43*(7), 1432-1436.

Faigenbaum, A. D., & Liatsos, N. S. (1994). The use and abuse of weightlifting belts. *Strength and Conditioning Journal, 16*(4), 60-62.

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.

Fletcher, I. M., & Bagley, A. (2014). Changing the stability conditions in a back squat: the effect on maximum load lifted and erector spinae muscle activity. *Sports Biomechanics, 13*(4), 380-390.

Fry, A., Aro, T., Bauer, J., & Kraemer, W. (1993). A comparison of methods for determining kinematic properties of three barbell squat exercises. *Journal of Human Movement Studies, 24*(2), 83.

Gamble, P. (2012). *Strength and conditioning for team sports: sport-specific physical preparation for high performance*. New York: Routledge.

Garhammer, J. (1980). Power production by Olympic weightlifters. *Medicine and Science in Sports and Exercise, 12*(1), 54-60.

Garhammer, J. (1989). Weight lifting and training. *Biomechanics of sport*, 169-211.

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, 10*, 10.

Goodin, J. (2015). *Comparison of external kinetic and kinematic variables between high barbell back squats and low barbell back squats across a range of loads* (Masters Thesis). East Tennessee State University, Tennessee.

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.

Gourgoulis, V., Aggeloussis, N., Antoniou, P., Christoforidis, C., Mavromatis, G., & Garas, A. (2002). Comparative 3-dimensional kinematic analysis of the snatch technique in elite male and female greek weightlifters. *Journal of Strength and Conditioning Research, 16*(3), 359-366.

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.

Hales, M. E., Johnson, B. F., & Johnson, J. T. (2009). Kinematic analysis of the powerlifting style squat and the conventional deadlift during competition: is there a cross-over effect between lifts? *Journal of Strength and Conditioning Research, 23*(9), 2574-2580.

Hamlyn, N., Behm, D. G., & Young, W. B. (2007). Trunk muscle activation during dynamic weight-training exercises and isometric instability activities. *Journal of Strength and Conditioning Research, 21*(4), 1108-1112.

Han, S., Ge, S., Liu, H., & Liu, R. (2013). Alterations in three-dimensional knee kinematics and kinetics during neutral, squeeze and outward squat. *Journal of Human Kinetics, 39*(1), 59-66.

Harman, E., & Frykman, P. (1990). The effects of knee wraps on weightlifting performance and injury. *National Strength and Conditioning Association Journal, 12*(5), 30-35.

Harman, E. A., Rosenstein, R. M., Frykman, P. N., & Nigro, G. A. (1989). Effects of a belt on intra-abdominal pressure during weight lifting. *Medicine and Science in Sports and Exercise, 21*(2), 186-190.

Hashemi Oskouei, A., 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.

Hooper, D. R., Szivak, T. K., Comstock, B. A., Dunn-Lewis, C., Apicella, J. M., Kelly, N. A., . . . Volek, J. S. (2014). Effects of fatigue from resistance training on barbell back squat biomechanics. *Journal of Strength and Conditioning Research, 28*(4), 1127-1134.

International Powerlifting Federation. (2015). *Technical Rules Book*. Retrieved from http://www.powerlifting-ipf.com/fileadmin/ipf/data/rules/technical-rules/english/2015_V2_IPF_Technical_Rules_Book_2015_classic_rules_in_back_section.pdf

International Weightlifting Federation. (2015). *Technical and Competition Rules & Regulations 2013-2016*. Retrieved from http://www.iwf.net/wp-content/uploads/downloads/2015/01/IWF-TCRR-2013-2016.2015.01.22.pdf

Jidovtseff, B., Harris, N. K., Crielaard, J. M., & Cronin, J. B. (2011). Using the load-velocity relationship for 1RM prediction. *Journal of Strength & Conditioning Research, 25*(1), 267-270. doi:10.1519/JSC.0b013e3181b62c5f

Katsavelis, D., & Joseph Threlkeld, A. (2014). Quantifying thigh muscle co-activation during isometric knee extension contractions: Within- and between-session reliability. *Journal of Electromyography and Kinesiology, 24*(4), 502-507. doi:10.1016/j.jelekin.2014.04.004

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.

Kellis, E., Arambatzi, F., & Papadopoulos, C. (2005). Effects of load on ground reaction force and lower limb kinematics during concentric squats. *Journal of Sports Sciences, 23*(10), 1045-1055. doi:10.1080/02640410400022094

Kingma, I., Faber, G. S., Suwarganda, E. K., Bruijnen, T. B., Peters, R. J., & van Dieen, J. H. (1976). Effect of a stiff lifting belt on spine compression during lifting. *Spine, 31*(22), E833-839.

Kobayashi, Y., Kubo, J., Matsuo, A., Matsubayashi, T., Kobayashi, K., & Ishii, N. (2010). Bilateral asymmetry in joint torque during squat exercise performed by long jumpers. *Journal of Strength and Conditioning Research, 24*(10), 2826-2830. doi:10.1519/JSC.0b013e3181c64387

Kram, R., Griffin, T. M., Donelan, J. M., & Chang, Y. H. (1998). Force treadmill for measuring vertical and horizontal ground reaction forces. *Journal of Applied Physiology, 85*(2), 764-769.

Kurustien, N., Mekhora, K., Jalayondeja, W., & Nanthavanij, S. (2014). Trunk stabilizer muscle activity during manual lifting with and without back belt use in experienced workers. *Journal of the Medical Association of Thailand, 97*(7), S75-79.

Lake, J., Lauder, M., Smith, N., & Shorter, K. (2012). A comparison of ballistic and nonballistic lower-body resistance exercise and the methods used to identify their positive lifting phases. *Journal of Applied Biomechanics, 28*(4), 431-437.

Lake, J. P., Carden, P. J. C., & 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.

Lander, J. E., Bates, B. T., & Devita, P. (1986). Biomechanics of the squat exercise using a modified center of mass bar. *Medicine and Science in Sports and Exercise, 18*(4), 469-478.

Lander, J. E., Hundley, J. R., & Simonton, R. L. (1992). The effectiveness of weight-belts during multiple repetitions of the squat exercise. *Medicine and Science in Sports and Exercise, 24*(5), 603-609.

Lander, J. E., Simonton, R. L., & Giacobbe, J. K. F. (1990). The effectiveness of weight-belts during the squat exercise. *Medicine and Science in Sports and Exercise, 22*(1), 117-126.

Lawrence, M. A., & Carlson, L. A. (2015). Effects of an unstable load on force and muscle activation during a parallel back squat. *Journal of Strength and Conditioning Research.*

Maddigan, M. E., Button, D. C., & Behm, D. G. (2014). Lower-limb and trunk muscle activation with back squats and weighted sled apparatus. *Journal of Strength and Conditioning Research, 28*(12), 3346-3353. doi:10.1519/jsc.0000000000000697

Matuszak, M. E., Fry, A. C., Weiss, L. W., Ireland, T. R., & McKnight, M. M. (2003). Effect of rest interval length on repeated 1 repetition maximum back squats. *Journal of Strength and Conditioning Research, 17*(4), 634-637. doi:10.1519/00124278-200311000-00002

McBride, J. M., Cormie, P., & Deane, R. (2006). Isometric squat force output and muscle activity in stable and unstable conditions. *Journal of Strength and Conditioning Research, 20*(4), 915-918.

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.

McCurdy, K., O'Kelley, E., Kutz, M., Langford, G., Ernest, J., & Torres, M. (2010). Comparison of lower extremity emg between the 2-leg squat and modified single-leg squat in female athletes. *Journal of Sport Rehabilitation, 19*(1), 57-70.

McGill, S. M., Norman, R. W., & Sharratt, M. T. (1990). The effect of an abdominal belt on trunk muscle activity and intra-abdominal pressure during squat lifts. *Ergonomics, 33*(2), 147-160.

McKean, M. R., Dunn, P. K., & Burkett, B. J. (2010). Quantifying the movement and the influence of load in the back squat exercise. *Journal of Strength and Conditioning Research, 24*(6), 1671-1679.

McKenzie, C., Brughelli, M., Whatman, C., & Brown, S. (2015). The influence of optimal handheld load on the technical ability to apply ground reaction forces during horizontal jumping in female netball players. *International Journal of Sports Medicine, 37*(4), 318-323. doi:10.1055/s-0035-1565052

McLaughlin, T. M., Dillman, C. J., & Lardner, T. J. (1977). Kinematic model of performance in the parallel squat by champion powerlifters. *Medicine and Science in Sports, 9*(2), 128-133.

Medina, J. M., McKeon, P. O., & Hertel, J. (2006). Rating the levels of evidence in sports-medicine research. *Athletic Therapy Today, 11*(5), 38-41.

Miletello, W. M., Beam, J. R., & Cooper, Z. C. (2009). A biomechanical analysis of the squat between competitive collegiate, competitive high school, and novice powerlifters. *Journal of Strength and Conditioning Research, 23*(5), 1611-1617. doi:10.1519/JSC.0b013e3181a3c6ef

Miyamoto, K., Iinuma, N., Maeda, M., Wada, E., & Shimizu, K. (1999). Effects of abdominal belts on intra-abdominal pressure, intra-muscular pressure in the erector spinae muscles and myoelectrical activities of trunk muscles. *Clinical Biomechanics, 14*(2), 79-87.

Mutchler, J. A., Weinhandl, J. T., Hoch, M. C., & Van Lunen, B. L. (2015). Reliability and fatigue characteristics of a standing hip isometric endurance protocol. *Journal of Electromyography and Kinesiology.* doi:10.1016/j.jelekin.2015.02.003

Newton, H. (2002). *Explosive lifting for sports*. Champaign, IL: Human Kinetics.

Nisell, R., & Ekholm, J. (1986). Joint load during the parallel squat in powerlifting and force analysis of in vivo bilateral quadriceps tendon rupture. *Scandinavian Journal of Sports Sciences, 8*(2), 63-70.

Nuzzo, J. L., McCaulley, G. O., Cormie, P., Cavill, M. J., & McBride, J. M. (2008). Trunk muscle activity during stability ball and free weight exercises. *Journal of Strength and Conditioning Research, 22*(1), 95-102.

Olstad, B. H., Zinner, C., Cabri, J., & Kjendlie, P.-L. (2014). Surface electromyographic measurements on land prior to and after 90 min of submersion (swimming) are highly reliable. *Journal of Electromyography and Kinesiology, 24*(5), 698-703. doi:10.1016/j.jelekin.2014.06.006

O'Shea, P. (1985). Sports Performance Series: The parallel squat. *National Strength and Conditioning Association Journal, 7*(1), 4.

Palmitier, R. A., An, K. N., Scott, S. G., & Chao, E. Y. (1991). Kinetic chain exercise in knee rehabilitation. *Sports Medicine, 11*(6), 402.

Panissa, V. L. g., Azevedo Neto, R. M., Julio, U. F., Pinto E Silva, C. M., & Franchini, E. (2013). Maximum number of repetitions, total weight lifted and neuromuscluar fatigue in indiiduals with different training backgrounds. *Biology of Sport, 30*(2), 131-136.

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.

Pereira, G. R., Lepobace, G., Chagas, D. D. V., Furtado, L. F. L., Praxedes, J., & Batista, L. A. (2010). Influence of hip external rotation on hip adductor and rectus femoris myoelectric activity during a parallel squat. *Journal of Strength and Conditioning Research, 24*(10), 2749-2754.

Pick, J., & Becque, M. D. (2000). The relationship between training status and intensity on muscle activation and relative submaximal lifting capacity during the back squat. *Journal of Strength and Conditioning Research, 14*(2), 175-181.

Pincivero, D. M., Aldworth, C., Dickerson, T., Petry, C., & Shultz, T. (2000). Quadriceps-hamstring EMG activity during functional, closed kinetic chain exercise to fatigue. *European Journal of Applied Physiology, 81*(6), 504-509.

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.

Renfro, G. J., & Ebben, W. P. (2006). A review of the use of lifting belts. *Strength and Conditioning Journal, 28*(1), 68-74.

Renström, P., Arms, S., Stanwyck, T., Johnson, R., & Pope, M. (1986). Strain within the anterior cruciate ligament during hamstring and quadriceps activity*. *The American Journal of Sports Medicine, 14*(1), 83-87.

Robertson, D. G. E., Wilson, J.-M. J., & Pierre, T. A. S. (2008). Lower extremity muscle functions during full squats. *Journal of Applied Biomechanics, 24*(4), 333-339.

Salem, G. J., Salinas, R., & Harding, F. V. (2003). Bilateral kinematic and kinetic analysis of the squat exercise after anterior cruciate ligament reconstruction. *Archives of Physical Medicine and Rehabilitation, 84*(8), 1211-1216. doi:10.1016/S0003-9993(03)00034-0

Sands, W. A., McNeal, J. R., & Shultz, B. B. (1999). Kinetic and temporal patterns of three types of vertical jump among elite international divers. *Research in Sports Medicine: An International Journal, 9*(2), 107-127.

Sato, K., Fortenbaugh, D., & Hydock, D. S. (2012). Kinematic changes using weightlifting shoes on barbell back squat *Journal of Strength and Conditioning Research, 26*(1), 28-33.

Sato, K., Fortenbaugh, D., Hydock, D. S., & Heise, G. D. (2013). Comparison of back squat kinematics between barefoot and shoe conditions. *International Journal of Sports Science and Coaching, 8*(3), 571-578.

Sato, K., & Heise, G. D. (2012). Influence of weight distribution asymmetry on the biomechanics of a barbell back squat. *Journal of Strength and Conditioning Research, 26*(2), 342-349. doi:10.1519/JSC.0b013e318220e0a3

Schick, E. E., Coburn, J. W., Brown, L. E., Judelson, D. A., Khamoui, A. V., Tran, T. T., & Uribe, B. P. (2010). A comparison of muscle activation between a smith machine and free weight bench press. *Journal of Strength and Conditioning Research, 24*(3), 779-784. doi:10.1519/JSC.0b013e3181cc2237

Schoenfeld, B. J. (2010). Squatting kinematics and kinetics and their application to exercise performance. *Journal of Strength and Conditioning Research, 24*(12), 3497-3506.

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.

Sedliak, M., Finni, T., Peltonen, J., & Hakkinen, K. (2008). Effect of time-of-day-specific strength training on maximum strength and EMG activity of the leg extensors in men. *Journal of Sports Sciences, 26*(10), 1005-1014.

Senter, C., & Hame, S. L. (2006). Biomechanical analysis of tibial torque and knee flexion angle: implications for understanding knee injury *Sports Medicine, 36*(8), 635-641.

Shelbourne, K. D., Klootwyk, T. E., & DeCarlo, M. S. (1992). Update on accelerated rehabilitation after anterior cruciate ligament reconstruction. *Journal of Orthopaedic and Sports Physical Therapy, 15*(6), 303-308.

Signorile, J. F., Weber, B., Roll, B., Caruso, J. F., Lowensteyn, I., & Perry, A. C. (1994). An electromyographical comparison of the squat and knee extension exercises. *Journal of Strength and Conditioning Research, 8*(3), 178-183.

Sinclair, J., McCarthy, D., Bentley, I., Hurst, H. T., & Atkins, S. (2014). The influence of different footwear on 3-D kinematics and muscle activation during the barbell back squat in males. *European Journal of Sport Science*, 1-8. doi:10.1080/17461391.2014.965752

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology, 91*(1), 46-52.

Steindler, A. (1955). *Kinesiology of the human body under normal and pathological conditions*. Springfield: Charles C. Thomas.

Steinkamp, L. A., Dillingham, M. F., Markel, M. D., Hill, J. A., & Kaufman, K. R. (1993). Biomechanical considerations in patellofemoral joint rehabilitation. *The American Journal of Sports Medicine, 21*(3), 438-444.

Stone, M. H., Potteiger, J. A., Pierce, K. C., Proulx, C. M., O'Bryant, H. S., Johnson, R. L., & Stone, M. E. (2000). Comparison of the effects of three different weight-training programs on the one repetition maximum squat. *Journal of Strength and Conditioning Research, 14*(3), 332-337.

Stoppani, J. (2006). *Encyclopedia of muscle & strength*. Champaign, IL: Human Kinetics.

Storey, A., & Smith, H. K. (2012). Unique aspects of competitive weightlifting: Performance, training and physiology. *Sports Medicine, 42*(9), 769-790. doi:10.1007/bf03262294

Storey, A., Wong, S., Smith, H. K., & Marshall, P. (2012). Divergent muscle functional and architectural responses to two successive high intensity resistance exercise sessions in competitive weightlifters and resistance trained adults. *European Journal of Applied Physiology, 112*(10), 3629-3639.

Storey, A. G., Birch, N. P., Fan, V., & Smith, H. K. (2015). Stress responses to short-term intensified and reduced training in competitive weightlifters. *Scandinavian Journal of Medicine & Science in Sports, 26*(1), 29-40. doi:10.1111/sms.12400

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.

Totten, L. (1990). Knee wraps. *National Strength and Conditioning Association Journal, 12*(5), 36-38.

Toutoungi, D., Lu, T., Leardini, A., Catani, F., & O'Connor, J. (2000). Cruciate ligament forces in the human knee during rehabilitation exercises. *Clinical Biomechanics, 15*(3), 176-187.

van den Tillaar, R., Andersen, V., & Saeterbakken, A. H. (2014). The existence of a sticking region in free weight squats. *Journal of Human Kinetics, 42*(1), 63-71.

van Ingen Schenau, G. J., Bobbert, M. F., & de Haan, A. (2010). Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics, 13*(4).

Varghese, R., Hui-Chan, C. W. Y., Wang, E., & Bhatt, T. (2014). Internal consistency and test–retest reliability of an instrumented functional reaching task using wireless electromyographic sensors. *Journal of Electromyography and Kinesiology, 24*(5), 593-600. doi:10.1016/j.jelekin.2014.05.011

Warren, L. P., Appling, S., Oladehin, A., & Griffin, J. (2001). Effect of soft lumbar support belt on abdominal oblique muscle activity in nonimpaired adults during squat lifting. *Journal of Orthopaedic and Sports Physical Therapy, 31*(6), 316-323.

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.

Willardson, J. M., Fontana, F. E., & Bressel, E. (2009). Effect of surface stability on core muscle activity for dynamic resistance exercises. *International Journal of Sports Physiology and Performance, 4*(1), 97-109.

Wilson, G. J., Lyttle, A. D., Ostrowski, K. J., & Murphy, A. J. (1995). Assessing dynamic performance: A comparison of rate of force development tests. *Journal of Strength & Conditioning Research, 9*(3), 176-181.

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & posture, 3*(4), 193-214.

Wisløff, 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.

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.

Wretenberg, P., Feng, Y., Lindberg, F., & Arborelius, U. P. (1993). Joint moments of force and quadriceps muscle activity during squatting exercise. *Scandinavian Journal of Medicine and Science in Sports, 3*(4), 244-250.

Yack, H. J., Collins, C. E., & Whieldon, T. J. (1993). Comparison of closed and open kinetic chain exercise in the anterior cruciate ligament-deficient knee. *The American Journal of Sports Medicine, 21*(1), 49-54.

Yavuz, H. U., Erdağ, D., Amca, A. M., & Aritan, S. (2015). Kinematic and EMG activities during front and back squat variations in maximum loads. *Journal of Sports Sciences*, 1-9. doi:10.1080/02640414.2014.984240

Zink, A. J., Perry, A. C., Robertson, B. L., Roach, K. E., & Signorile, J. F. (2006). Peak power, ground reaction forces, and velocity during the squat exercise performed at different loads. *Journal of Strength and Conditioning Research, 20*(3), 658-664.

Zink, A. J., Whiting, W. C., Vincent, W. J., & McLaine, A. J. (2001). The effects of a weight belt on trunk and leg muscle activity and joint kinematics during the squat exercise. *Journal of Strength and Conditioning Research, 15*(2), 235-240.

Zourdos, M. C., Klemp, A., Dolan, C., Quiles, J. M., Schau, K. A., Jo, E., . . . Blanco, R. (2015). Novel resistance training-specific RPE scale measuring repetitions in reserve. *Journal of Strength and Conditioning Research*. doi:10.1519/jsc.0000000000001049

APPENDICES

Appendix 1: Ethics approval, Auckland University of Technology Ethics Committee

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

17 November 2015

Adam Storey
Faculty of Health and Environmental Sciences

Dear Adam

Re: Ethics Application: **14/398 An analysis of high-bar and low-bar back-squat techniques in Olympic weightlifters and power-lifters.**

Thank you for your request for approval of an amendment to your ethics application.

I have approved the minor amendment to your ethics application allowing an additional control group.

I remind you that as part of the ethics approval process, you are required to submit the following to the Auckland University of Technology Ethics Committee (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 15 December 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 15 December 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.

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: Daniel Glassbrook daniel.glassbrook@gmail.com, Allan Carman; Scott Brown; Eric Helms; Kelly Sheerin

Appendix 2: Participant information sheet

Participant Information Sheet

Date Information Sheet Produced:

18/11/14

Project Title

An analysis of high-bar and low-bar back-squat techniques in Olympic weightlifters and power-lifters.

An Invitation

Hi, my name is Daniel Glassbrook and I am a Masters student at AUT University. I would like to personally invite you to assist in my project that aims to determine the difference between high-bar and low-bar back-squats and their influence on Olympic weightlifting performance.

It is entirely your choice as to whether you participate in the project or not. If you decide you no longer want to participate you are free to withdraw yourself or any information that you have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way. Your consent to participate in this research will be indicated by your signing and dating the consent form. Signing the consent form indicates that you have read and understood this information sheet, freely given your consent to participate, and that there has been no coercion or inducement to participate by the researchers from AUT.

What is the purpose of this research?

The squat is a common exercise used in strength and conditioning, and in both Olympic weightlifting, and power-lifting. Traditionally however, a high-bar back-squat style is used by Olympic weightlifters and a low-bar back-squat style is used by power-lifters. The purpose of this research is to compare the two styles of back-squat in terms of kinetics (force outputs), kinematics (joint angles and technique variations), and EMG (muscle activity). Currently there is little research that has specifically compared the two kinds of back-squat, especially beyond 70% of one repetition maximum. These results will help us to better understand he differences between high-bar and low-bar back-squats and this could lead to education regarding exercise prescription for athletes and the general population in New Zealand. Also, a comparison between the high and low-bar back-squats and the Olympic weightlifts has not been performed. Therefore, we will also test the snatch, and clean and jerk in order to be able to understand how the two types of squat could affect performance in the Olympic weightlifts.

Each participant will gain a personalised athletic assessment regarding their performances, snatch, clean and jerk and high-bar back-squat for Olympic weightlifters, low-bar back-squats for power-lifters, and both-high-bar and low-bar back squats for the recreationally trained control group. The researchers will benefit also, as this is a novel, applied research study. New knowledge for researchers and practitioners will be gained looking into the differences between high-bar and low-bar back-squats and how this influences snatch and clean and jerk performance in Olympic weightlifters.

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

You are eligible to participate in this study if you are (1) a male between the ages of 18 and 35 years; (2) have ≥ 1 year of strength training experience consisting of ≥ 3 training sessions per week; (3) free from acute or chronic injury at the time of the training intervention, and (4) satisfy the minimum requirements for C-grade Olympic weightlifting and/or Bronze grade power-lifting within New Zealand or (5) are a recreationally trained athlete completing > 1 back-squat training per week over at least the last year, and (6) can squat between 1.25 and 1.75 times your body weight.

What will happen in this research?

Once you have decided to participate in the study you will be asked to visit our exercise laboratory for one 3-hour testing session, if you are a powerlifter or a recreationally trained athlete, or twice (one 3-hour session and one 2-hour session) if you are an Olympic weightlifter. Recreationally trained athletes will also be asked to undertake two 1-hour familiarisation sessions in the week prior to the testing date, at AUT-Millennium.

<u>Session 1 (3 hours), Olympic weightlifters, powerlifters, and controls.</u>

You will arrive at AUT-Millennium campus SPRINZ testing facility where you will have a full anthropometric assessment. You will also be given a complete verbal familiarisation of the testing procedures and equipment followed by a visual demonstration. Following a standardised dynamic warm-up, you will be fitted with reflective markers on selected body locations, and surface electromyography (EMG) sensors. Upon completion of the EMG setup, you will be required to perform a maximal test of the high-bar back-squat if you are an Olympic weightlifter, of the low-bar back-squat if you are a powerlifter, or both back-squats if you are a recreationally trained control. You will be asked to complete several sub-maximal back-squat at 50, 60, 70, 80, and 90% of your current one repetition maximum, prior to attempting to match or exceed your current one repetition maximum. All attempts will be performed whilst standing on two embedded force platforms, and each attempt recorded for each lift. Additionally, all attempts will be recorded using a nine-camera, three-dimensional motion capture system to process kinematic data. Recorded footage will contain segment and joint trajectory data only and will not identify participant characteristics (i.e. 2D video and photographs).

<u>Control group familiarisation sessions (two 1-hour sessions).</u>

If you are a recreationally trained athlete, and part of the control group, you will complete two 1-hour familiarisation sessions within the week prior to the testing. These sessions are intended to familiarize you with both back-squat variations, prior to a maximal test of each back-squat. The first of these sessions will comprise of the same standardized dynamic warm up, and one repetition maximum testing protocol that will be completed in the testing session, however you will only work up to 60% of your predicted one repetition maximum in both back-squats. Two days later, the second familiarisation session will follow the same format, and during this session you will work up to 80% of your predicted one repetition maximum for both back-squats. The final testing session will be completed three days after the second familiarisation session during which time you will perform a maximal effort in both the high bar and low bar back squat. The order that these lifts will be performed, will be randomly selected prior to your first familiarisation session, and kept for all three sessions.

Session 2 (2 Hours), Olympic weightlifters only.

After the same standardised dynamic warm-up, you will be fitted with reflective markers on selected body locations, and surface electromyography sensors. You will then be asked to perform several sub-maximal snatches at 60, 70, 80 and 90% of your current one repetition maximum, before completing a one repetition attempt at your current one repetition maximum for the snatch. The same protocol will then be repeated for the clean and jerk. All attempts will be performed whilst standing on a single embedded force platform, within a special lifting platform, and each attempt recorded for each lift.

What are the discomforts and risks?

You will be asked to perform some sub-maximal (moderate intensity) and maximal (very heavy intensity) exercise during the data collection and therefore during the latter could potentially experience discomfort for a short period of time towards the concluding minutes of these maximal assessments. The intensity of the exercise will be similar to what is felt in training and competition situations.

How will these discomforts and risks be alleviated?

Being an experienced athlete who regularly competes and is familiar with training at high intensities, the exercise trials will be similar to what you have experienced within a typical week to week training and competition program. If you are experiencing discomfort at any stage you are encouraged to inform the researcher with you at the time in order that they can best address the problem. If you have any questions regarding and risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

What are the benefits?

Each participant will gain a personalised athletic assessment regarding their performances in the clean and jerk, snatch and/or back-squat(s). The researchers will benefit also, as this is a novel, applied research study. New knowledge for researchers and practitioners will be gained looking into the differences between high-bar and low-bar back-squats and how this influences clean and jerk and snatch performance on Olympic weightlifters. The wider sporting community will be educated as to differences between high-bar and low-bar back-squats and this could lead to education regarding exercise prescription for athletes in New Zealand.

The results of this research are intended for publication and will contribute to part of my master's thesis and will also be submitted to peer-reviewed journals for publication.

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 the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Your privacy will be protected by data being de-identified (coded numbers i.e. ID 123 instead of your name to be used throughout), and the researcher will not disclose anyone's participation in this study. All participant data will be averaged and represented as group means. No names or pictures will be used in reporting (unless the participant gives explicit additional written consent for media purposes following AUT protocols and organised via the AUT university relations team). During the project, only the applicant and named investigators will have access to the data collected. The results of the study may be used for further analysis and submission to peer-reviewed journals or submitted at conferences. To maintain confidentiality, in all publications resulting from this research participants' data will be averaged and represented as group means.

All data will be stored on password protected computers or in locked files. Following completion of data analysis your data will be stored by the AUT University SPRINZ research officer in the AUT University SPRINZ secure Ethics and Data facility at AUT Millennium campus for ten years. Following the ten-year storage period all hard copies of data will be destroyed (shredded) and electronic data will be wiped.

What are the costs of participating in this research?

There will be no financial cost for you being involved with this study. If you are an Olympic weightlifter, the first session will take approximately three hours, and then if you decide to take part in the second testing session, another two hours will be required seven days later at the same time of day. If you are a powerlifter, testing will take approximately three hours in total. If you are a control group, the testing will take approximately five hours all together, with two 1-hour familiarisation sessions, and one 3-hour testing session.

You will receive a $20 petrol voucher as koha for travel reimbursement to testing sessions.

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within two weeks whether you would be available to take part in the study or not. After consideration you may withdraw your participation at any time.

How do I agree to participate in this research?

If you agree to participate please fill in the attached consent form and return to me, Daniel Glassbrook.

Will I receive feedback on the results of this research?

Yes, each participant will gain a personalised athletic assessment regarding their performances in the clean and jerk, snatch and/or back-squat(s). It is your choice whether you share this information with your coach or other people.

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, *Dr. Adam Storey, adam.storey@aut.ac.nz, 021 2124200.*

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

Whom do I contact for further information about this research?

Researcher Contact Details:

Daniel Glassbrook

daniel.glassbook@gmail.com

027 956 5101

Project Supervisor Contact Details:

Dr Adam Storey
Sport Performance Research Institute New Zealand (SPRINZ), School of Sport and Recreation, Faculty of Health and Environmental Sciences, AUT University, Private Bag 92006, Auckland 1020,
adam.storey@aut.ac.nz, 021 2124200.

Approved by the Auckland University of Technology Ethics Committee on *19 November 2015,* AUTEC Reference number *14/398*

Appendix 3: Participant consent form

Consent Form

For use when laboratory or field testing is involved.

AUT UNIVERSITY

Project title: An analysis of high-bar and low-bar back-squat techniques in Olympic weightlifters and power-lifters.

Project Supervisor: Dr Adam Storey

Researcher: ***Daniel Glassbrook***

- O I have read and understood the information provided about this research project in the Information Sheet dated 20th November 2014.
- O I have had an opportunity to ask questions and to have them answered.
- O 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.
- O I am not suffering from any current injury or illness that may impair my ability to perform the required tasks nor am I outside the limits of the required age range of 18 to 35 years.
- O I agree to answer questions and provide physical effort to the best of my ability throughout testing.
- O I agree to take part in this research.
- O I wish to receive a copy of the report from the research (please tick one): YesO NoO

Participant's signature:

....

Participant's name:

....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 15 December 2014 AUTEC Reference number 14/398.

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

Appendix 4: Recruitment flyer 1: Olympic weightlifters and powerlifters

SPORTS PERFORMANCE
RESEARCH INSTITUTE, NEW ZEALAND
AN INSTITUTE OF AUT UNIVERSITY

AUT UNIVERSITY

Invitation to Olympic Weightlifters and Power-lifters

Hi, my name is Daniel Glassbrook and I am a Masters student at AUT University. I would like to personally invite you to assist in my project that aims to determine the difference between high-bar and low-bar back-squats and their influence on Olympic weightlifting performance.

Eligibility Criteria:

- Male aged between 18-35 years,
- Free from acute or chronic injury,
- A current competitive Olympic weightlifter (C grade and above), or power-lifter (bronze grade and above).

OWNZ	Weight Class (kg)	56	62	69	77	85	94	105	105+	
	Lifted Total (kg)	155	167	182	195	205	215	225	240	
NZPF	Weight Class (kg)	53	59	66	74	83	93	105	120	120+
	Lifted Total (kg)	327.5	360	392.5	427.5	480	510	540	565	585

What the research will involve:

2-3 visits to the SPRINZ Laboratory at AUT Millennium for:

- Full anthropometric assessment,
- Full 3D analysis of the snatch, clean and jerk and high-bar back-squat (Olympic weightlifters) or low-bar back-squat (power-lifters) at 60, 70, 80, 90 and 100% of your 1RM.

Time required:

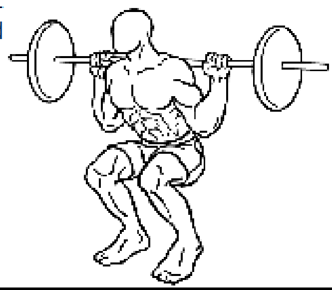
- 2-3 hours in total.

Benefits to the athlete:

Each participant will gain a personalised athletic assessment regarding their performances, snatch, clean and jerk and high-bar back-squat for Olympic weightlifters, or low-bar back-squats for power-lifters. You will receive a $20 petrol voucher as koha for travel reimbursement to testing sessions.

Would you like to participate?

If you would like to find out more information or register your interest to take part in this study, please contact me for a detailed participant information sheet and consent form.



Thank you for your consideration.

Daniel Glassbrook BSR, PGDip.Sp&Ex, Masters Candidate Sport Science. Sports Performance Research Institute New Zealand I AUT University AUT Millennium, 17 Antares Place, Mairangi Bay, 0632, NZ.

Email: daniel.glassbrook@gmail.com I Mobile: 0279565101

Appendix 5: Recruitment flyer 2: Control group

SPORTS PERFORMANCE
RESEARCH INSTITUTE, NEW ZEALAND
AN INSTITUTE OF AUT UNIVERSITY

Are you interested in the science of lifting large?

We are conducting a study here at AUT-Millennium that you may qualify for!

- Are a **Male** who is **18-35** years old?
- Can back-squat **between 1.25 and 1.75 times** your body weight,
- Don't use anabolic steroids or any other WADA banned substances,
- Are healthy and not currently diagnosed with any serious medical conditions,
- Are currently squatting **at least once a week** in training, and can donate **3 hours of your time?**

Then you qualify to participate in a study on the high-bar and low-bar back-squat techniques!

Each participant will receive a **personalised back-squat analysis.** Joint angles, force production and muscle activation levels will be measured throughout both the low-bar and high-bar back-squats. This information can be useful for your next competition build up, or to get more out of your training!

Whom do I contact for further information about this research?

Researcher **Daniel Glassbrook**	Project supervisor **Dr Adam Storey**
PH: 027 956 5101	PH: 021 212 4200
E: daniel.glassbrook@gmail.com	E: adam.storey@aut.ac.nz

Appendix 6: Dynamic warm up routine

1: 10 Leg swings front and back

2: 10 Trunk twists

3: 10 Body weight squats

4: 10 Press-ups

5: 10 Wrist rotations clockwise & 10 Wrist rotations anti-clockwise

6: 5 'T's

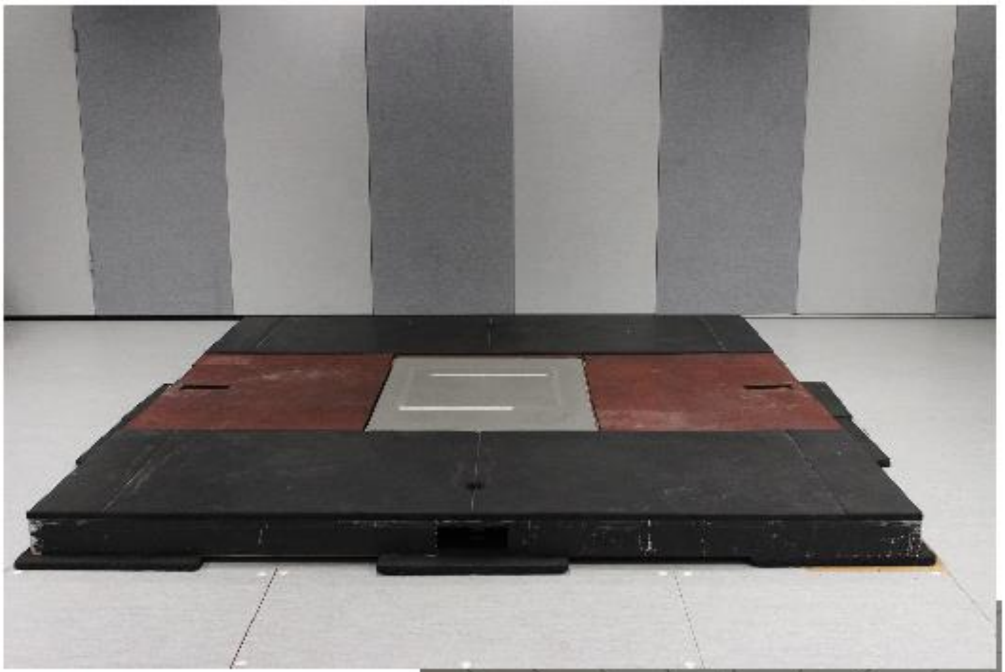
7: 5 'Y's

Appendix 7: Resistance exercise-specific rating of perceived exertion (RPE) scale

Resistance Exercise-Specific Rating of Perceived Exertion (RPE)

Rating	*Description of Perceived Exertion*
10	*Maximum effort*
9.5	*No further repetitions but could increase load*
9	*1 repetition remaining*
8.5	*1-2 repetitions remaining*
8	*2 repetitions remaining*
7.5	*2-3 repetitions remaining*
7	*3 repetitions remaining*
5-6	*4-6 repetitions remaining*
3-4	*Light effort*
1-2	*Little to no effort*

Appendix 8: Experimental set up



Top: Olympic weightlifting platform, fitted with single AMTI force platform (Model ACP, Advanced Mechanical Technology, Inc., Watertown, Massachusetts, USA).

Right: Two embedded force platforms (Model AM6501, Bertec Corp., Columbus, Ohio, USA), for back-squat performance. Olympic weightlifting platform in background.