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Comparison of External Kinetic and Kinematic Variables between High Barbell Back Squats and Low Barbell Back Squats across a Range of Loads

Jacob Goodin
East Tennessee State University

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by
Jacob Richard Goodin
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Brad DeWeese, EdD, Committee Chair
Kimitake Sato, PhD, Committee Member
Satoshi Mizuguchi, PhD, Committee Member
Ashley Kavanaugh, PhD, Committee Member

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ABSTRACT

Comparison of External Kinetic and Kinematic Variables between High Barbell Back Squats and Low Barbell Back Squats across a Range of Loads

by

Jacob R. Goodin

This study compared peak force, peak power, peak velocity, impulse, work, and vertical displacement between the high bar back squat (HBBS) and low bar back squat (LBBS). Six trained males performed each using 20, 30, 40, 50, 60, 70, 80, and 90% of their recent training 1 repetition maximum. Dual force plates recorded force-time curve characteristics of ground reaction forces and four potentiometers tracked vertical and horizontal barbell displacement. Repeated–measures analysis of variance revealed a significant main effect for load ($p<0.01$) across all variables, but no significant effects for condition or interaction. The HBBS generated higher peak force in loads 20%–80%, higher peak power in loads 20%–60% and 80%–90%, higher peak velocity at every load, and greater vertical displacement at every load. The LBBS generated a larger impulse at loads 30%-90% and the HBBS generated more work at loads 20%, 40%, and 60%–90%.

DEDICATION

I dedicate this thesis first to God, within whom I live and move and have my being. Secondly, I dedicate this to my wife Lisa, who has graciously supported me through the entire research process and all of the set-backs, missed deadlines, and sleepless nights that went along with it. She is a blessing to me second only to my salvation in Christ.

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CHAPTER 1

INTRODUCTION

Statement of Problem

The squat is referred to by many strength coaches and sport scientists as the "most important" (Comfort & Kasim, 2007, p. 10) or "king" (O'Shea, 1985, p. 4) of resistance training exercises for the development of lower body strength (Clark, Lambert, & Hunter, 2012; Escamilla, 2001a; Fry, Aro, Bauer, & Kraemer, 1993; Fry, Smith, & Schilling, 2003; Gullet, Tillman, Gutierrez, & Chow, 2009; McCaw & Melrose, 1999; Paoli, Marcolin, & Petrone, 2009; Schoenfeld, 2010; Wretenberg, Feng, & Arborelius, 1996; P Wretenberg, Feng, & Lindberg, 1993). A large body of literature has reported its effectiveness across multiple populations including untrained (Candow & Burke, 2007), adolescent (Comfort, Stewart, Bloom, & Clarkson, 2014), geriatric (Hagerman et al., 2000), rehabilitative (Escamilla, 2001a; Schoenfeld, 2010), and athletic populations. The most common squat styles are the high bar back squat (HBBS) and the low bar back squat (LBBS). A steadily growing body of research has examined the HBBS (Bryanton, Kennedy, Carey, & Chiu, 2012; Fry et al., 2003; Gullet et al., 2009; Sato, Fortenbaugh, Hydock, & Heise, 2013) and LBBS (Escamilla, 2001a; Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; Escamilla et al., 1998) separately, and some effort has been made to compare muscle activation, kinetic, and kinematic variables between the two conditions (Benz, 1989; Clark et al., 2012; Fry et al., 1993; Schoenfeld, 2010; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012; Wretenberg et al., 1996). Influential coaches (Rippetoe & Kilgore, 2007) and sport scientists (M. H. Stone, personal communication, December 3, 2014) interpret the existing evidence differently in regard to the two conditions' application to sport, illustrating a need for greater elucidation of their underlying differences. It is not yet clear if the external kinetic and kinematic variables of the HBBS and LBBS are similar at given loads or if they respond similarly to changes in load. Small improvements in strength and related strength characteristics, while not statistically significant, may hold practical significance for elite athletes whose competition is often decided by hundredths of a second (Mujika, Padilla, Pyne, & Busso, 2004). Therefore, the purpose of this study is to use a crossover design and absolute loads to examine the load– and condition– dependent trends of selected external kinetic and kinematic performance variables in the HBBS and LBBS in order to further inform coaches and sport scientists as they make exercise selection and variation decisions for athletes. For the remainder of this manuscript, "HBBS" will refer to high bar back squats and "LBBS" will refer to low bar back squats. When the specific variation of back squat is neither specified by the authors nor deducible from their description, the term "back squat" will be used.

Definitions

1. Barbell back squat: A traditional resistance training exercise where the lifter begins the movement while standing upright with the barbell resting across the shoulders before flexing at the hip, knee and ankle joints to descend into a squat. Upon reaching the desired depth, the lifter reverses the motion by extending at the hip and knee joints and plantar flexing at the ankle joint to return to standing (Schoenfeld, 2010).

2. High bar back squat (HBBS): A variation of the barbell back squat used by Olympic style weightlifters due to its upright torso posture in which the barbell rests just inferior to the 7th cervical vertebrae and superior to the acromion (Donnelly, Berg, & Fiske, 2006; Schoenfeld, 2010; Wretenberg et al., 1996)

3. Low bar back squat (LBBS): A variation of the barbell back squat favored by powerlifters for enabling them to lift heavier weights in competition where the bar is placed

below the acromion (Schoenfeld, 2010), across the spine of the scapula (Wretenberg et al., 1996), or two inches below the superior aspect of the shoulders (O'Shea, 1985).

4. Allometric scaling: A technique used to normalize strength measures for comparison between individuals of varying body mass using the formula [$y=x\cdot(BdM^{/3})^{-1}$] where y = allometrically scaled mass, BdM = body mass in kilograms, and x=dependent variable (Challis, 1999; Kraska et al., 2009).

5. Sticking region: The region of minimum bar velocity in a dynamic movement, typically corresponding with the point of lowest mechanical advantage (Hales, Johnson, & Johnson, 2009; Michael RM McGuigan & Wilson, 1996)

6. Rate of force development: measure of the rate of rise of contractile force development during muscular contraction that is expressed in Newtons per second ($N\cdot S^{-1}$). Can be measured in individual fibers, muscles, or multi-joint movements and calculated at various time-points using the force-time curve (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002).

7. Linear position transducer: A device that uses a potentiometer and extendable wire affixed to a moving object to determine said object’s position in one dimension.

Significance of Study

Strength and conditioning professionals frequently prescribe back squats to athletes due to their biomechanical sport specificity (Escamilla, Fleisig, Zheng, et al., 2001; Senter & Hame, 2006); high transfer of training effect to athletic movements (Cormie, McCaulley, & McBride, 2007; Cormie, McGuigan, & Newton, 2010a); and the strong correlations observed between squatting ability and variables that may predict athletic performance in a range of athletic activities (Comfort et al., 2014; Sleivert & Taingahue, 2004; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004).

The high bar and low bar variations of the back squat are the most commonly implemented squat variations in training and most thoroughly described variations in the literature, though to date only four studies have directly compared the two conditions. Benz (1989) was the first to document significant differences in trunk inclination between the HBBS and LBBS, and found that the absolute torso angle was greater in the HBBS than the LBBS. Fry et al. (1993) filmed 6 weight-trained males while they performed the front squat, HBBS, and LBBS. Using 2-dimensional video analysis they observed on average that at the lowest point of vertical displacement the LBBS exhibited greater forward trunk inclination and more vertical shank angles than the HBBS. Although not statistically significant, this data agrees with that of Benz (1989). Wretenberg et al. (1996) examined EMG data from three upper leg muscles and the joint moments of force in the knee and hip in national level weightlifters (HBBS group) and powerlifters (LBBS group) during squats to parallel and full depth. They reported an evenly distributed moment of force between the hip and knee in the weightlifters, with the powerlifters exhibiting greater hip loads and also higher muscle activation in the vastus lateralis, rectus femoris, and biceps femoris. However, due to the lack of a crossover design, these findings may have been influenced by the large discrepancies in age (weightlifters: 18.9±3.0 years, powerlifters 30.8 ± 3.1 years) and squat to body mass ratios (weightlifters: 1.9xbody mass ± 0.4, powerlifters 3.0xbody mass ± 0.5) between the two groups. Swinton et al. (2012) compared the biomechanics and external kinetics of the HBBS, LBBS, and box squat using a group of well-trained powerlifters. Their findings agreed with previous research (Escamilla, Fleisig, Lowry, et al., 2001), demonstrating a wider self-selected stance width, greater hip flexion angles, smaller plantarflexion angles, larger hip extension moments, and smaller dorsiflexion moments in the LBBS when compared to the HBBS.

Despite the various authors' agreement concerning the biomechanics of the HBBS and LBBS among these four studies, further work must be done to fully elucidate the external kinetic and kinematic differences between HBBS and LBBS, especially as they relate to athletic performance. It is well known that the ability to produce high peak and mean power outputs is essential to most forms of sport (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Carlock et al., 2004; Cronin & Hansen, 2005; Sleivert & Taingahue, 2004; Stone et al., 2006), and thus so is the enhancement of these and related variables, such as rate of force development, peak force, peak velocity, and impulse. Furthermore, many authors have begun identifying other external kinetic and kinematic variables derived from isometric and dynamic force-time curves as being moderate to strong correlates with performance indices such as jump height, sprint, and agility performance (G. G. Haff et al., 2005; Kraska et al., 2009; Jeffrey M McBride, Triplett-McBride, Davie, & Newton, 2002; Stone et al., 2004). Their findings suggest that comparative knowledge of these external performance variables (such as rate of force development at critical time points, allometrically-scaled peak force, and impulse) in the HBBS and LBBS would be valuable to coaches and sport scientists when prescribing squat variations to athletes. The study by Swinton et al. (2012) investigated several external performance variables (peak force, peak velocity, peak power, and rate of force development), however found no significant differences in these variables between HBBS and LBBS. This may have been due to a small sample size (n=8) or insufficient loading (30%, 50%, and 70% of LBBS 1 repetition maximum) not extensive or challenging enough to uncover existing trends. Given these observations and the relative paucity of comparative kinetic and kinematic performance data, further research is warranted.

Purpose of Study

The purpose of this study was to compare how peak force, peak power, peak velocity, impulse, work, and vertical displacement in the concentric phase of the HBBS and LBBS responded to changes in load in young resistance-trained males. The loads lifted in both the HBBS and LBBS conditions were 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of each individual's HBBS one repetition maximum (1 repetition maximum). A crossover design and absolute loads were used in an effort to eliminate previously identified confounding factors such as subject differences or a load effect.

Hypothesis

This study is a hypothesis-generating exploratory study, the goal of which is to observe each condition in a controlled setting to report any differences or similarities between them. Thus the results of this study will be used primarily to guide further inquiry into fully understanding these two conditions and their place in athletic preparation, and secondarily to help inform sport scientists and coaches in exercise selection and variation decisions.

Assumptions

1. All subjects adhered to the conditions provided in the Informed Consent Document.
2. All subjects answered the health history questionnaire truthfully.

Delimitations

The delimitations in this study were that each subject must have at least 2 years of squatting experience (using either HBBS, LBBS, or both) and a HBBS 1 repetition maximum equal to 1.5 x body mass (body mass) resistance or greater. Participants also must have completed 8 filmed practice sessions for the HBBS and LBBS in the weeks leading up to their first testing session. All subjects were undergraduate and graduate aged male students (18-28 years).

Limitations

The primary limitation to this study was the small sample size (n = 6), leading to low statistical power and low probability of finding statistical significance. Another limitation was that each subject had more experience with either the HBBS or LBBS. Thus any differences between conditions could be partially attributed to a skill component.

CHAPTER 2

REVIEW OF THE LITERATURE

Role of the Back Squat in Athletic Preparation

In sport, the barbell back squat serves as a physical preparation exercise for Olympic style weightlifters, strength and power athletes, sprinters, and endurance athletes, perhaps because of the well-documented positive influence that maximal strength has on rate of force development and the ability to generate power (Aagaard et al., 2002; Cormie, McCaulley, & McBride, 2007; Cormie, McCaulley, Triplett, & McBride, 2007; Cormie et al., 2010a; Cormie, McGuigan, & Newton, 2010b) and the roles that power production and rate of force development play in sport (Nimphius, McGuigan, & Newton, 2010; Sleivert & Taingahue, 2004). The back squat is also one of the three competition movements for powerlifters.

Correlations Between Back Squat Performance and Measures of Strength and Power

Soviet sport scientists Laputin, Charniga, and Oleshko (1986) detailed the periodization and programming of the preeminent Soviet weightlifting program, and noted that HBBSs accounted for about 20% of the national team’s lifters monthly training volume from 1977-1980, second only to the snatch (27%) and clean and jerk (26%). They also established percentage tables charting the HBBS 1 repetition maximum as a percentage of clean and jerk 1 repetition maximum across each weight class and performance group. They observed that although light weight classes had higher HBBS to clean and jerk ratios than middle and heavy weight classes, more advanced athletes displayed stronger negative correlations ($r = -0.86$) between HBBS 1 repetition maximum percentage ratios and body mass than less advanced athletes ($r = -0.61$). Overall, the Soviet lifters displayed strong correlations ($r = 0.65$) between the HBBS and competition lifts. Essentially, squatting strength was a primary exercise in the Soviet program during their period of world weightlifting dominance—even more so for athletes who were more advanced or in lighter weight classes—second only to technique work in the competition lifts. Much later Stone et al. (2005) discussed relationships between maximal strength and clean 1 repetition maximum in 65 male and female junior and senior national class American weightlifters, finding strong relationships between HBBS 1 repetition maximum and the snatch and clean and jerk using a variety of absolute and relative scaling measures (r = 0.80 to 0.95).

The back squat has also been shown to correlate with performance measures in strength and power athletes. This may be due in part to the aforementioned relationship between maximal strength and power, as demonstrated in a study by Kraska et al. (2009). The group collected data as part of an ongoing athlete-monitoring program overseeing the physical preparedness of NCAA Division I collegiate male and female athletes participating in track and field, tennis, softball, soccer, and volleyball (n = 63). Isometric peak force achieved in an isometric mid-thigh pull showed significant moderate to strong correlations with loaded and unloaded static and countermovement jumps (r = 0.36 to 0.55). Wisløff et al. (2004) tested elite male Norwegian soccer players' (n = 17) and found that maximal strength (half squat 1 repetition maximum) correlated strongly with 10m and 30m sprint times, 10m shuttle time, and countermovement vertical jump height (r = 0.94, 0.71, 0.68, and 0.78, respectively, p < 0.01). Ten female softball players from the Australian Institute of Sport participated in a study by Nimphius et al. (2010) that found only moderate correlations between relative strength (back squat 1 repetition maximum/body mass) and countermovement vertical jump height pre, mid, and post season (r = 0.36, 0.38, and 0.16 respectively), but strong correlations between relative strength and a range of sprint and agility performance variables (r = -0.5 to -0.87). Another study by M. R. McGuigan, Winchester, and Erickson (2006) found that mid thigh pull isometric peak force correlated strongly with back squat 1 repetition maximum in a group of 10 NCAA Division III wrestlers. These findings agree with previous research by W. J. Kraemer et al. (2001) stating that maximal strength is a primary performance-influencing variable in wrestling. This sampling of strength and power sports examples displays the importance of maximal strength across differing athletic populations and that the back squat is a reliable measure of maximal strength.

In addition to strength/power sports, exposure to maximal strength training may lead to improvements in endurance performance. Stone et al. (2006, pp. 44, 45) defined endurance as "the ability to maintain or repeat a given force or power output" and strength as "the ability to produce force." Thus it follows that increases in an athlete's peak force would lead to decreases in the effort required to sustain the submaximal forces and power outputs found in endurance sports. These principles are demonstrated in work by Storen, Helgerud, Stoa, and Hoff (2008), who assigned three sessions/week of half squats to four male and four female elite runners (VO_{2max}=61.4±5.1 $mL \cdot kg^{-1} \cdot min^{-1}$). After 8 weeks they found significant improvements in half squat 1 repetition maximum and rate of force development, as well as running economy, maximal aerobic speed, and time to exhaustion.

The Back Squat as a Stimulus for Strength and Power Adaptations

The back squat is a staple exercise in strength and conditioning programs, a reliable test of maximal strength, and strong correlate with athletic performance, but the neural and muscular mechanisms by which it increases strength and power are the same as those of general resistance training. The following section will briefly review the physiological and mechanical underpinnings of the relevant strength and power characteristics before examining the barbell back squat's effectiveness in enhancing these characteristics.

Neural adaptations to resistance training include a functional adaptations such as lowered activation threshold of high threshold motor units (Baechle & Earle, 2008; Wuerker, McPhedran, & Henneman, 1965), greater EMG muscle activation and faster rate coding (Andersen & Aagaard, 2006; Viitasalo & Komi, 1981), increased agonist activation and synchronization (Felici et al., 2001; Milner-Brown, Stein, & Lee, 1975), and decreased antagonist co-contraction (Carolan & Cafarelli, 1992); and structural changes such as increased myelination (Asensio-Pinilla, Udina, Jaramillo, & Navarro, 2009), increased dendritic complexity and length (Ploughman, 2008; Redila & Christie, 2006; van Praag, Shubert, Zhao, & Gage, 2005), increases in axon diameter (Edds, 1950; Wedeles, 1949), and morphological changes to the neuromuscular junction including increased endplate perimeter and length and concentration of acetylcholine receptors (Deschenes et al., 2000). Muscular adaptations to resistance training include increased cross-sectional area, altered biochemical response, enhanced muscle architecture, and fiber type transitions (Bazyler, 2013; Stone, Stone, Sands, & Sands, 2007). There is an order to the time course of adaptation in that strength gains are primarily due to neural changes during the first ten weeks of training, and afterward increases in cross-sectional area account for further increases in strength (Sale, 1988; Stone et al., 2007).

A number of inter-related factors contribute to the direction and magnitude of these adaptations, including periodization variables such as training emphasis, intensity, frequency, volume, and duration; programming variables such as exercise selection, and set, rep, and rest scheme; individual variables such as genotype, phenotype, and training status; and outside factors such as outside stressors, nutrition, and concurrent training and recovery modalities (Bazyler, 2013; W. J. Kraemer & Ratamess, 2004; Plisk & Stone, 2003; Stone et al., 2007). Of particular importance in this discussion are exercise selection and its relation to exercise intensity and volume in an athlete's resistance training program. Exercise selection encompasses factors such as biomechanical specificity, open– versus closed–chain movements, movement pattern variation, and targeted muscle group and muscle fiber development (MacKenzie, Lavers, & Wallace, 2014). According to Stone et al. (1998, p. 22), exercise intensity is the power output associated with a movement (the product of force and velocity or alternatively work divided by time) and volume is defined as "the amount of work performed per set, per exercise, per day." By this definition, exercise intensity is distinct from but related to both relative intensity and training intensity. Relative intensity is the fraction of 1 repetition maximum of a given lift used during training (expressed as a percent), and training intensity is the rate at which a training session proceeds (expressed as kilograms lifted per second) (Stone et al., 1998).

Exercise selection, volume, and intensity can all be manipulated to achieve a desired training goal. Strength endurance and increased cross-sectional area are best stimulated with large muscle mass exercises and high volume (Dudley, Tesch, Miller, & Buchanan, 1991; Hather, Tesch, Buchanan, & Dudley, 1991; W. Kraemer et al., 1995; William J Kraemer, 1997; Marx et al., 1998; Sanborn et al., 2000; Stone, O'Bryant, Garhammer, McMillan, & Rozenek, 1982; Stone et al., 1998). Maximal strength requires high training intensity and sufficient volumes of high relative intensity lifting (Behm, 1995; Dudley et al., 1991; Kramer et al., 1997; Stone et al., 1998) Improvements in power, speed, and rate of force development require exercises with a high degree of mechanical and velocity specificity (Häkkinen, 1994; Stone, 1993; Stone et al., 1998) to the task. Furthermore, in non-linear periodization training schemes these emphases rotate in a cyclical manner throughout an annual competition cycle so that exercise selection, volume, and intensity vary between mesocycles (Andersen et al., 2005; Issurin, 2008; Matveyev, 1966; Monteiro et al., 2009; Plisk & Stone, 2003). For example, a sprinter may perform full range of motion Olympic pulling movements during a strength endurance phase when increased cross-sectional area is the emphasis and accruing training volume is important, but substitute mid-thigh pulling movements during the competition phase when fatigue management and fitness expression are the emphasis and a reduction in volume and increase in intensity are required (Andersen et al., 2005; Plisk & Stone, 2003).

In general, exercise selection is manipulated to control volume and intensity in a way that maximizes gains and minimizes fatigue. Resistance training movements are chosen based on their mechanical and metabolic sport–specificity, the individual athlete's needs, and the context of the programing and periodization scheme. However, the magnitude of adaptation is partially dependent on the product of volume and intensity at which an athlete can train over time, and it has been shown that training at higher volumes and intensities yields larger gains in strength and related abilities (Stone et al., 1998; Wernbom, Augustsson, & Thomee, 2007), especially in the lower body (Paulsen, Myklestad, & Raastad, 2003). The interaction of these three variables is partially responsible for training outcomes.

The barbell back squat is an ideal exercise for increasing lower body strength and power because it is a closed kinetic chain (Escamilla et al., 1998; Schoenfeld, 2010; Stone, Collins, Plisk, Haff, & Stone, 2000), free-weight (Schwanbeck, Chilibeck, & Binsted, 2009; Stone, Collins, et al., 2000), large muscle mass (Clark et al., 2012), large range-of-motion (Escamilla, Fleisig, Lowry, et al., 2001), bilateral exercise with a high degree of sport specificity (MacKenzie et al., 2014; Schoenfeld, 2010). These qualities make it an ideal stimulus and primary exercise to drive the aforementioned neural and muscular adaptations and thereby improve athletic strength and power.

Closed kinetic chain movements (in which the peripheral segments are fixed) are superior to open movements (in which the peripheral segments move freely) in eliciting positive training adaptations (Stone, Collins, et al., 2000) because they have a higher degree of joint motion and muscle recruitment specificity (Blackburn & Morrissey, 1998; Palmitier, An, Scott, & Chao, 1991). Furthermore, closed kinetic chain exercises tend to also be large muscle mass, multiple joint exercises (such as the barbell back squat), while many open kinetic chain exercises “isolate” a specific joint or muscle group to produce a single joint movement or constrain the movement pattern to a fixed trajectory (such as a knee extension machine). Large muscle mass exercises create a larger stimulus for adaptation due to increased muscle mass recruitment and have a higher transfer of training effect because their kinetic and kinematic profile is more similar to athletic movements than small muscle mass exercises (Blackburn & Morrissey, 1998; Palmitier et al., 1991). Some exercises are both closed kinetic chain and recruit a large muscle mass but utilize a machine that constrains the movement pattern to a fixed track (such as the Smith machine back squat). The fixed nature of machine-based exercises greatly decreases the demands of the target musculature (G Gregory Haff, 2000; Schwanbeck et al., 2009). Finally, exercises that allow for large displacements of load and joint ranges of motion place a greater stimulus on the musculature, increasing total muscular tension and time under tension, two important factors in the development of hypertrophy and maximal strength (Shoenfeld, 2010)

In a comparison between an 8 repetition–maximum in the free standing back squat (closed kinetic chain, large muscle mass, free-weight exercise) and Smith machine back squat (closed kinetic chain, large muscle mass, machine-based exercise) Schwanbeck et al. (2009) found the free standing barbell back squat elicited significantly higher electromyographic activity in the gastrocnemius (34%), biceps femoris (26%), and vastus medialis (49%).

Furthermore, average total electromyographic activity (tibialis anterior, gastrocnemius, vastus medialis, vasuts lateralis, biceps femoris, lumbar erector spinae, and rectus abdomus) was 43% higher in the free standing back squat than the Smith machine back squat. Both Signorile, Kwiatkowski, Caruso, and Robertson (1995) and Escamilla et al. (1998) found that the barbell back squat generated significantly higher hamstring and quadriceps muscle activity than knee extensions or the leg press machine. Blackburn and Morrissey (1998) measured vertical and horizontal jump performance and found strong correlations to squatting performance (vertical: r = 0.722, horizontal: r = 0.650), but weak correlations with isotonic knee extension performance (vertical: r = 0.097, horizontal: r = 0.070). Augustsson, Esko, Thomeé, and Svantesson (1998) prescribed 6 weeks of machine-based open kinetic chain training (knee extension and hip abduction variable resistance machine) or free-weight closed kinetic chain training (barbell back squat) to two groups of young men. In a 3 repetition maximum squat test the two groups improved by 31% and 13% (closed kinetic chain and open kinetic chain, respectively), and in a vertical jump test only the closed kinetic chain group showed significant improvement (10%).

In summary, the barbell back squat can stimulate large neural and muscular adaptations because is a closed kinetic chain, large muscle mass, multiple joint movement with a high degree of mechanical specificity to athletic movements. It challenges the hip, knee, and ankle joints through a large range of motion and can be performed with high load and low velocity or low load and high velocity according to an athlete’s needs. The barbell back squat is a highly effective exercise for improving lower body strength, power, and rate of force development because of these characteristics, and its importance and widespread use make it of interest to coaches and sport scientists to more fully understand the underling external kinetic and kinematic differences between the primary squat variations.

Squat Variations

Many squatting variations exist, each with a unique biomechanical profile. Although this thesis will focus on the HBBS and LBBS, it is important to consider broadly the extent of variation within bilateral squat patterns, as this may help to inform the questions discussed in this text and gives a context for the HBBS and LBBS. The following three barbell squat variations are commonly used by weightlifers, powerlifters, and athletes.

The front squat is used primarily as a weightlifting assistance exercise to strengthen the catch phase of the clean (Garhammer, 1993) and also by athletes as a compliment to or in place of back squats (Gullet et al., 2009). The barbell is placed over the anterior deltoids with the hands in a loose pronate grip and the elbows lifted up and forward. Because the external load rests on the anterior side of the lifter's torso, the front squat has a significantly larger absolute torso angle than either the HBBS or LBBS (Fry et al., 1993) and significantly lower extensor moments and compressive forces at the knee than HBBS using a relative load (Gullet et al., 2009). It is also thought by strength and conditioning coaches that due to the bar placement, flexion moments acting along the spine are lower in the lumbar region and higher in the thoracic region than back squats, however no research has examined this specifically.

The box squat is unique among squatting variations in that it dissipates the elastic energy return from the stretch shortening cycle (J. M. McBride, Skinner, Schafer, Haines, & Kirby, 2010) while also enabling greater posterior displacement of the hip and center of mass (Swinton et al., 2012). The lifter places the barbell in a LBBS position and squats down and back to a box, shifting their center of mass behind their base of support to pause for 1-3 seconds on the box (J. M. McBride et al., 2010; Rippetoe & Kilgore, 2007; Swinton et al., 2012). This pause is responsible for the decrease in elastic energy return, but also for dramatically increased rate of force development during the concentric phase compared to the traditional back squat, because the lifter must initiate concentric movement from an essentially unloaded position (Swinton et al., 2012). The box squat is commonly by powerlifters to teach posterior hip displacement and train an explosive drive at the start of the concentric phase (Swinton, Lloyd, Agouris, & Stewart, 2009).

The overhead squat involves holding a barbell overhead with fully extended elbows and a snatch-width grip. The bar stays in this position as the lifter descends into a deep squat and returns to standing. The notion that the overhead squat requires significantly greater activation of the anterior trunk musculature than the back squat (Brown, 2006; Hasegawa, 2004) was challenged by Aspe and Swinton (2014). They compared electromyography activity in the back squat, overhead squat, and four trunk isolation exercises and found that activation of the rectus abdominis during a 90% relative load was significantly higher in the overhead squat than the back squat, but only by 2-7%. In contrast, the four trunk isolation exercises all showed significantly higher electromyography activity in rectus abdominis by a margin of about 10-30% (interpreted visually from a graphical representation of the data).

General Characteristics of the High Bar Back Squat and Low Bar Back Squat

Bar Placement

The HBBS or “Olympic style” squat is used commonly by weightlifters, strength/power athletes, and some powerlifters and is characterized by a narrow stance and upright torso, with the bar placed on top of the trapezius near the 7th cervical vertebrae (Fry et al., 2003; Hatfield, 1981; Schoenfeld, 2010; Wretenberg et al., 1996). The resulting upright trunk position more closely resembles movements performed in weightlifting (Wretenberg et al., 1996) and the vertical jump, which are important trainable positions for weightlifters and other strength and power athletes. The LBBS is frequently used by powerlifters because some believe that it allows for increased loading (Rippetoe & Kilgore, 2007; Swinton et al., 2009) due to a greater reliance on the musculature of the posterior chain (Escamilla, 2001a; Escamilla, Fleisig, Lowry, et al., 2001; Escamilla, Fleisig, Zheng, et al., 2001; Rippetoe & Kilgore, 2007; Schoenfeld, 2010).

Powerlifters are unique in that the back squat is one of their three competition lifts, along with the deadlift and bench press. Unlike athletes who employ squats as a means to develop strength that transfers to sport specific positions, powerlifters can maximize force generation by adopting whichever technique allows them to lift the most weight. Data collected by Escamilla, Fleisig, Lowry, et al. (2001) from the American Drug-Free Powerlifting Association masters level national powerlifting championship divided 39 competitors evenly into three groups based on self-selected stance width: narrow stance (87-118% shoulder width), medium stance (121-153% shoulder width), and wide stance (158-196% shoulder width). Interestingly, in terms of absolute load, the medium stance group outperformed the narrow stance group, and the wide stance group had the highest performance, though it should also be noted that the mean body mass of the lifters increased from the narrow to medium to wide stance groups. Although this paper does not specify bar placement, the kinematic joint data suggests that the medium and wide stance groups used a LBBS technique due to their smaller plantarflexion angles and greater hip flexion angles (Swinton et al., 2012).

The LBBS stance width is variable and forward trunk inclination is more pronounced (Escamilla, Fleisig, Lowry, et al., 2001; Schoenfeld, 2010). Precise bar placement in the LBBS varies in the literature, from on top of the posterior deltoids and inferior to the scapular spine (Fry et al., 1993; Hatfield, 1981), to across the scapular spine (Wretenberg et al., 1996), to two inches below the shoulders (O'Shea, 1985).

Stance Width

Although no stance width constraints exist in either condition, certain trends can be observed and deduced. Escamilla, Fleisig, Lowry, et al. (2001) observed LBBS stance width to range from 97-183% of shoulder width in well-trained powerlifters during competition. HBBS stance width has been reported as shoulder width (Chandler & Stone, 1992; Fry et al., 2003), though anecdotal evidence suggests that width may vary from this position but rarely reaches the width found in some powerlifters who use the LBBS (Escamilla, Fleisig, Lowry, et al., 2001; Swinton et al., 2012).

Trunk and Knee Position

Forward trunk inclination is more pronounced in the LBBS, with many authors noting low absolute torso angles compared with other squat variations or squats with a narrow stance (Benz, 1989; Escamilla, Fleisig, Lowry, et al., 2001; Fry et al., 2003; Rippetoe & Kilgore, 2007; Schoenfeld, 2010). This forward inclination likely contributes to the greater hip extensor and lower knee extensor torques found in several studies (Fry et al., 2003; Schoenfeld, 2010; Watkins, 1999; Wretenberg et al., 1996). Forward translation of the knee likely increases knee extensor torque (Fry et al., 2003), and among powerlifters, those with a narrow stance (more similar to a HBBS stance) experienced 4-6 cm greater forward knee translation, (Escamilla, Fleisig, Lowry, et al., 2001). The HBBS allows for a more upright trunk position (Benz, 1989; Schoenfeld, 2010; Wretenberg et al., 1996), possibly due to greater forward knee translation and reliance on the knee extensor musculature (Fry et al., 2003; Wretenberg et al., 1996). This in turn has been associated with lower hip extensor torque and greater knee extensor torque (Fry et al., 2003; Schoenfeld, 2010; Swinton et al., 2012; Watkins, 1999; Wretenberg et al., 1996)

Foot Rotation

Several authors have investigated the effects of foot rotation on muscle activation in the back squat. Collectively they found that altering the angle of the feet via tibial rotation caused no significant changes in muscle activation of the quadriceps, gluteus maximus, hamstrings, or gastrocnemius from 30 degrees of internal rotation to 80 degrees of external rotation in either condition (Hsieh & Walker, 1976; Miyamoto, Iinuma, Maeda, Wada, & Shimizu, 1999; Ninos, Irrgang, Burdett, & Weiss, 1997; Schaub & Worrell, 1995; Schoenfeld, 2010; Signorile et al., 1995).

Muscle Activation

Gastrocnemius activity progressively increases with an increasing knee angle, and its medial head acts as a knee stabilizer (Bell, Padua, & Clark, 2008; Donnelly et al., 2006; Escamilla, Fleisig, Lowry, et al., 2001). Vastus lateralis and vastus medialis showed little difference in activity levels as a percent of total electrical activity of four muscles (gluteus maximus and biceps femoris being the other two) during partial, parallel, and full squats in a study by Caterisano et al. (2002), though both are significantly more active than rectus femoris at a variety of stance widths and foot rotation angles (Escamilla, Fleisig, Zheng, et al., 2001). Gluteus maximus activity increases significantly during full squats when compared to half squats and parallel squats (Caterisano et al., 2002; Schoenfeld, 2010). Senter and Hame (2006) reported that biceps femoris is more active than semimembranosus or semitendinosus, and that because the hamstrings function as both hip extensors and knee flexors, their activity remains somewhat constant throughout the squat. Spinal integrity is maintained by the lumbar erector spinae, and thus activity of the lumber erector spinae increases as forward lean increases (Toutoungi, Lu, Leardini, Catani, & O'Connor, 2000).

Squat Depth

Caterisano et al. (2002) found that gluteus maximus activity increased significantly when squatting below parallel with a load equal to 100-125% of body mass, but found no change in biceps femoris, vastus lateralis, or vastus medialis activity. In a study comparing weightlifters and powerlifters, Wretenberg et al. (1996) found no difference in EMG activity or joint moments of force between squats to parallel and full squats in either the HBBS or LBBS condition. They did report a significant increase in rectus femoris activity in the powerlifter group, though this was likely a function of the greater body mass and absolute bar load of the powerlifting group (Clark et al., 2012). In contrast to this, another study found that thigh musculature activation was highest in the deepest 30 degrees of the squat for both the concentric and eccentric portions (Pereira et al., 2010). The most recent study by Bryanton et al. (2012) measured relative muscular effort of the plantar flexors, knee extensors, and hip extensors during the back squat at a variety of loads from 119 to 30 degrees of knee flexion. They found that knee and hip extensor relative muscular effort increased with greater squat depth, and that the plantar flexors and hip extensor relative muscular effort increased with increasing load.

External Kinetics

In both the HBBS and LBBS peak force increases with increasing load and peak velocity decreases with increasing load (Cormie, McCaulley, Triplett, et al., 2007; Kellis, Arambatzi, & Papadopoulos, 2005; Swinton et al., 2012). The load at which peak power is optimized is reported to be 45% of 1 repetition maximum in weightlifters and road cyclist (Izquierdo, Hakkinen, Gonzalez-Badillo, Ibanez, & Gorostiaga, 2002); 56% in NCAA Division I strength power athletes (Cormie, McCaulley, Triplett, et al., 2007); 60% in handball players, middle-distance runners, untrained men (Izquierdo et al., 2002) and middle-aged men (Izquierdo et al., 1999); and 70% in elderly men (Izquierdo et al., 2002). Swinton et al. (2012) found no significant differences between HBBS and LBBS in peak force, peak velocity, peak power, or rate of force development at 30%, 50%, and 70% of LBBS 1 repetition maximum in powerlifters, though peak velocity and power was marginally higher in the HBBS across all three loads. This may have been due to the randomized loading order, which has the potential to distribute fatigue unequally among the three conditions.

Problem

Although both the HBBS and LBBS conditions have been well researched, very little direct comparison data exists. To this date, four studies have directly compared the HBBS and LBBS. The first, by Benz (1989) used a high speed camera to gather joint angles during both conditions in eight men familiar with the LBBS. Later Fry et al. (1993) investigated the HBBS, LBBS, and front squat, using six weight-trained males. Both studies focused solely on joint and segment angles, with the primary finding being the greater forward inclination of the trunk during the LBBS condition. Wretenberg et al. (1996) employed a non-crossover design by using weightlifters for the HBBS condition and powerlifters for the LBBS condition. He found significant difference in hip, knee, and ankle moments between the conditions as discussed previously and slightly higher EMG activity in the LBBS. However large differences in body mass and squat 1 repetition maximum between the two groups may have confounded muscle activation and condition interaction (Wretenberg et al., 1996). Finally, Swinton et al. (2012) found in a crossover design of 8 powerlifters that the HBBS resulted in an anterior displacement of the system center of mass, while LBBS resulted in an posterior displacement. They confirmed previous findings concerning joint kinematics and kinetics (Wretenberg et al., 1996), with the exception that they saw no difference between HBBS and LBBS in torso angle.

These four studies have done much to illuminate the joint kinematic, joint kinetic, EMG, and descriptive profiles of the HBBS and LBBS, however, no significant findings have been published concerning external kinetic data over a range of loads that correspond to those frequently seen in athletes' training. It remains to be determined whether the HBBS and LBBS conditions behave differently in regards to velocity-load, power-load, and force-time characteristics. These differences are of great importance to sport scientists, coaches, and athletes because of the development and expression of velocity, power, and rate of force development at critical time points are of primary importance to sport performance (Nimphius et al., 2010; Sleivert & Taingahue, 2004; Stone, 2014),

Research Questions

In light of these problems, this study asks the following questions. Are there significant differences between conditions in peak force, peak power, peak velocity, impulse, concentric work, and vertical displacement? Is there an interaction effect between load and condition in any of these variables, and if so, which loads show the greatest effect? This thesis will begin an investigation into the external kinetics and kinematics of the HBBS and LBBS in an attempt to identify practically significant differences that will generate hypotheses for further research.

CHAPTER 3

COMPARISON OF EXTERNAL KINETIC AND KINEMATIC VARIABLES BETWEEN HIGH BARBELL BACK SQUATS AND LOW BARBELL BACK SQUATS ACROSS A RANGE OF LOADS

Original Investigation

J.R. Goodin[1], C.D. Bazyler[1], C. Bellon[1], B. DeWeese[1], S. Mizuguchi[1], K. Sato[1], A. Kavanaugh[1], M. H. Stone[1]

[1]Department of Exercise and Sport Science, East Tennessee State University

Corresponding Author:

Jacob Goodin

East Tennessee State University

PO Box 70654

Phone: (423) 439-4665

Email: jacobrgoodin@gmail.com

Comparison of External Kinetic and Kinematic Variables between High Barbell Back Squats and Low Barbell Back Squats across a Range of Loads

ABSTRACT

The purpose of this study was to compare the external kinetic and kinematic characteristics of the high bar back squat (HBBS) and low bar back squat (LBBS). Six well trained males practiced both barbell conditions for four weeks before performing each condition using 20, 30, 40, 50, 60, 70, 80, and 90% of their most recent training HBBS 1 repetition maximum on two separate days with seven days between testing sessions. Participants assumed self-selected stance widths for each condition and were instructed to lift the loads as fast as possible. Dual force plates recorded force-time curve characteristics of ground reaction forces and four potentiometers tracked vertical and horizontal barbell displacement. From these data six concentric variables were analyzed: peak force, peak power, peak velocity, impulse, work, and vertical displacement. A repeated–measures analysis of variance revealed a statistically significant main effect for load ($p<0.01$) across all variables, but no significant effects for condition or interaction. Although not statistically significant, the HBBS condition showed a trend towards higher peak force in loads 20%–80%, higher peak power in loads 20%–60% and 80%–90%, higher peak velocity at every load, and greater vertical displacement at every load. The LBBS showed a trend towards a larger impulse at loads 30%-90% and the HBBS showed a trend towards more work at loads 20%, 40%, and 60%–90%.

KEYWORDS: peak force, peak power, peak velocity, exercise selection

INTRODUCTION

Strength and power athletes and endurance athletes alike employ the back squat as a means to increase maximal strength and explosiveness that transfers into sport specific movements, while powerlifters practice it not only to increase maximal strength but as a component of their competition. Maximal strength is moderately to strongly correlated with a range of sport performance measures such as loaded and unloaded static and countermovement jump height in strength and power athletes (37, 73), sprint and change of direction performance variables in elite soccer and softball athletes (45, 73), rate of force development among multiple athletic populations (26, 37, 68), snatch and clean and jerk 1 repetition maximum in elite male and female weightlifters (38, 67), and sprint cycling times and wingate power in elite sprint cyclists (66). Improving maximal strength enhances these measures through various neural and muscular adaptations. Neural adaptations to resistance training include a lowered activation threshold of high threshold motor units (2, 75), greater electromyographic muscle activation and faster rate coding (1, 71), increased agonist activation and synchronization (21, 43), decreased antagonist co-contraction (10), and morphological changes to the neuromuscular junction (15). Muscular adaptations include increased cross-sectional area, altered biochemical response, enhanced muscle architecture, and fiber type transitions (3, 68).

The barbell back squat is an ideal exercise for promoting these neural and muscular adaptations because it is a closed kinetic chain (19, 55, 61), free-weight (56, 61), large muscle mass (12), large range-of-motion (18), bilateral exercise with a high degree of sport specificity (40, 55). Closed kinetic chain movements activate musculature to a higher degree than open kinetic chain and elicit greater adaptations in strength (61) because they have a higher degree of joint motion and muscle recruitment specificity (6, 47). They also tend to utilize a larger muscle mass and multiple joints (such as in the barbell back squat), while many open kinetic chain exercises isolate a specific joint or muscle group to produce a single joint movement while constraining the movement pattern to a fixed trajectory (such as a knee extension machine). Large muscle mass exercises create a larger stimulus for adaptation due to increased muscle mass recruitment and physiological demand (61) and have a higher transfer of training effect because their kinetic and kinematic profiles are more similar to athletic movements than small muscle mass exercises (6, 47). Some closed kinetic chain, large muscle mass exercises rely on a machine that constrains the movement pattern to a fixed track (such as the Smith machine back squat). The fixed nature of machine-based exercises greatly decreases the demands of the target musculature (25, 56). Finally, exercises that allow for large displacements of load and large joint ranges of motion place a greater stimulus on the musculature, increasing total muscular tension and time under tension, two important factors in the development of hypertrophy and maximal strength (57). It is for these reasons that the barbell back squat has long been considered a staple exercise for the development of lower body strength and explosiveness.

The two most common squatting styles are the high bar back squat (HBBS) and the low bar back squat (LBBS). The HBBS or “Olympic style” squat is used commonly by weightlifters, strength and power athletes, and some powerlifters and is characterized by a narrower stance and upright torso, with the bar placed on top of the trapezius near the 7th cervical vertebrae (24, 29, 55, 74). The resulting upright trunk position more closely resembles that found in weightlifting movements (74) and the vertical jump, which are important trainable positions for weightlifters and other strength and power athletes. The LBBS is frequently used by powerlifters because some believe that it allows for increased loading (52, 69) due to a greater reliance on the musculature of the posterior chain (17, 18, 20, 52, 55). The LBBS stance width is variable and forward trunk inclination is more pronounced (18, 55). Precise bar placement in the LBBS varies in the literature, from on top of the posterior deltoids, inferior to the scapular spine (23, 29), to across the scapular spine (74), to two inches below the shoulders (46).

A large steadily growing body of research surrounds these two squatting styles individually (7, 12, 17-19, 24, 49, 54, 55), and some effort has been made to compare muscle activation, kinetic, and kinematic variables between the two conditions (5, 23, 55, 70, 74). Benz (5) and Fry, Aro, Bauer and Kraemer (23) observed joint and segment angles, with the primary finding being the greater forward inclination of the trunk during the LBBS. Wretenberg, Feng and Arborelius (74) employed a non-crossover design by using weightlifters for the HBBS condition and powerlifters for the LBBS condition. He found significant differences between the weightlifters and powerlifters in moments at the hip (230 Nm and 324 Nm, respectively) and the knee (191 Nm and 139 Nm, respectively) and slightly higher peak electromyographic activity in the LBBS, though only the rectus femoris was statistically significant. However large differences in body mass and squat 1 repetition maximum between the two groups may have confounded muscle activation and condition interaction (74). Finally, Swinton, Lloyd, Keogh, Agouris and Stewart (70) found in a crossover design of 8 powerlifters that the HBBS resulted in an anterior displacement of the system center of mass, while LBBS resulted in a posterior displacement. They confirmed previous findings concerning joint kinematics and kinetics, with the exception that there was no significant difference between HBBS and LBBS in torso angle. The authors also reported peak force, peak power, peak velocity, and rate of force development. However because the results were not statistically significant they did not discuss the practical significance of the differences. These four studies have done much to illuminate the joint kinematic, joint kinetic, EMG, and descriptive profiles of the HBBS and LBBS. However, no significant findings have been published concerning external kinetic data over a range of loads that correspond to those frequently seen in athletes' training, leaving influential coaches (52) and sport scientists (M. H. Stone, personal communication, December 3, 2014) to interpret the existing evidence differently in regards to the two conditions' application to sport.

The back squat is a staple exercise in strength and conditioning programs, a reliable test of maximal strength, and strong correlate with athletic performance, but the neural and muscular mechanisms by which it increases strength and power are the same as those of general resistance training. A number of inter-related factors contribute to the direction and magnitude of these adaptations, including periodization variables such as training emphasis, intensity, frequency, volume, and duration; programming variables such as exercise selection, and set, rep, and rest scheme; individual variables such as genotype, phenotype, and training status; and outside factors such as outside stressors, nutrition, and concurrent training and recovery modalities (3, 35, 50, 68).

Exercise selection, volume, and intensity can all be manipulated to control the direction and magnitude of adaptation. For instance strength endurance and increased cross-sectional area are best stimulated with large muscle mass exercises and high volume (16, 30, 33, 34, 41, 53, 62, 63). Maximal strength requires high training intensity and sufficient volumes of high relative intensity lifting (4, 16, 36, 63). Improvements in power, speed, and rate of force development require exercises with a high degree of mechanical and velocity specificity (27, 59, 63) to the task. The magnitude of adaptation is partially dependent on the product of volume and intensity at which an athlete can train over time, and it has been shown that training at higher volumes and intensities yields larger gains in strength and related abilities (63, 72), especially in the lower body (48).

External kinetic and kinematic performance variables such as peak force, peak power, and peak velocity are all components or direct measures of exercise intensity, and vertical displacement is a component of volume load, which is often equated with work (36). Therefore, any differences in these variables between the HBBS and LBBS may have implications for athletes who desire to maximize neural and muscular adaptations and thereby improve strength and explosiveness.

It remains to be determined whether the HBBS and LBBS will display differences in how they respond to changes in load. These differences are of great importance to sport scientists, coaches, and athletes, because the development and expression of velocity, power, and rate of force development at critical time points are of primary importance to sport performance (45, 58, 60). Therefore the current study will attempt to answer several of these questions by comparing force and displacement data from the HBBS and LBBS across a range of loads. Specifically this study will investigate the trends between load and peak force, peak power, peak velocity, impulse, work, and vertical displacement in both the HBBS and LBBS.

METHODS

Experimental Approach to the Problem

A cross-sectional, repeated measures design was used to compare external kinematic and kinetic performance measures of the HBBS and LBBS within subjects. All subjects were experienced in both the HBBS or LBBS and completed 4 weeks of practice with both conditions prior to testing. Data were collected during 1 familiarization session and 2 testing sessions separated by 2-7 days and 7 days respectively. All sessions were performed in the laboratory.

Subjects

Six weight-trained males (age: 25.0 ± 3.1 years; height: 1.777 ± 0.038 ; squatting experience 7.5 ± 4.1 years; HBBS 1 repetition maximum: 157 ± 15.3 kg, 1 repetition maximum/body mass ratio: 1.8 ± 0.18) from weightlifting, powerlifting, and strength and power sport backgrounds familiar with HBBS and LBBS were recruited for this study. Only males with at least two years of squatting experience, a HBBS 1 repetition maximum to body mass ratio of at least 1.5, no health contraindications, and who had completed a 4 week HBBS and LBBS practice period were allowed to participate. Written informed consent was obtained from the subjects and approval was granted from East Tennessee State University's Institutional Review Board.

Procedures

Participants' standing height and seated height were measured to the nearest 0.5 cm using an electronic stadiometer (Cardinal Scale, Model DHRWM, Webb City, MO). Additionally, a 50.5 cm tall plyometric box pushed flush with the stadiometer was used during seated height measurements, with subjects seated back so that their sacral vertebrae touched the stadiometer. Body mass was measured with a calibrated digital scale certified to the nearest 0.1 kg (Tanita BF-350, Arlington Heights, IL). Dual uniplanar force plates with a sampling frequency of 1,000 Hz (0.91 m x 0.91 m; Rice Lake Weighing Systems, Rice Lake, WI, USA) were placed inside the squat rack to collect kinetic data during all squat sets. Both force plates were calibrated prior to each testing session. Four linear position transducers sampling at 1,000 Hz (Celesco Measurement Specialties, Chatsworth, CA, USA) were used to derive vertical and horizontal bar displacement by mounting one on each top corner of the power rack, with the front units and back units equidistant from the center. In this way the length of the linear position transducer represented the hypotenuse of a triangle, with vertical and horizontal displacement making up the other two sides. Given that the lengths of the front and back linear position transducer cables were equal when the barbell was centered, displacement could be calculated through trigonometric derivation. All kinetic and kinematic data were analyzed using Labview software (ver. 2010, National Instruments, Austin, TX, USA).

High bar back squat 1 repetition maximums were estimated for each subject based on their most recent training repetition maximum using the prediction equation by Brzycki (8) and validated by LeSuer, McCormick, Mayhew, Wasserstein and Arnold (39). Each subject completed four HBBS and four LBBS practice sessions over the course of four weeks prior to testing, with one session of each condition per week. Week 1 began with subjects completing one set of three reps at 10%, 20%, 30%, 40%, 50%, and 60% of their most recent HBBS 1 repetition maximum or estimated 1 repetition maximum. Each consecutive week added another set of three squats at a higher intensity so that by the fourth week each subject completed eight sets of three with each condition, one set at each load up to 90% of HBBS 1 repetition maximum. Loads for both the HBBS and LBBS sessions were calculated using HBBS 1 repetition maximums since, anecdotally, LBBS 1 repetition maximums are higher than HBBS 1 repetition maximumS and thus the subjects may not be able to complete 3 repetitions at the heavier loads. Participants filmed the last set of each practice session perpendicular to the sagittal plane and submitted it electronically to the authors for review. Feedback was administered to subjects concerning proper technique for each condition based on their individual errors, if they existed. All subjects were instructed to “allow forward translation of the knees” in the HBBS (24, 70) “maintain vertical shins while moving the hips posteriorly” in the LBBS (70).

Upon completion of the practice sessions each subject took part in one familiarization session and two data collection sessions. Data collection session 1 took place 2-7 days after the familiarization session and data collection session 2 took place exactly 7 days after data collection session 1. The familiarization session included height and weight measurements, stance-width measurements, equipment familiarization, warm-up and testing protocol familiarization. The standard warm-up protocol used for the familiarization and data collection sessions was 15 meters of forward walking lunges, reverse walking lunges, right and left side lunges, walking quad stretch, and walking hamstring stretch followed by five slow bodyweight squats and five fast bodyweight squats. After a three minute rest one of the conditions was selected at random and the subject performed three reps at 20%, 30%, 40%, and 50% of HBBS 1 repetition maximum. Two minutes rest was given between each set. Stance width was measured as the distance between medial malleoli and taken during the 20% set for each condition after the subject unracked the barbell. Once loads 20–50% were completed, the subject rested for five minutes for ecological validity and repeated the protocol with the second squatting condition.

Before each set the subject was reminded to perform the concentric portion of the squat as explosively as possible. They were instructed to un-rack the barbell and step onto the middle of the force plates and stand still. The command “squat!” signaled the start of each repetition, and verbal encouragement was offered for each of the three reps. The subject was made to stand still for two to three seconds between each rep and before racking the barbell to establish baseline displacement and force values for each rep. Squat depth and eccentric tempo was not controlled for because these may differ between squatting styles.

During data collection session 1 subjects completed the same warm-up protocol followed by three squats at 20, 30, 40, 50, 60, 70, 80, and 90% of HBBS 1 repetition maximum using the same squatting style that was performed first during the familiarization session. Pilot testing revealed that subjects self-selected two minutes or less rest time after loads 20–40%, therefore each subject was allowed two minutes of rest after loads 20–40%, and three to four minutes after 50–80% loads due to the increasing intensity of each set. During the 80% and 90% loads two spotters were used. Data collection session 2 followed the same protocol but with the second squatting style.

Statistical Analyses

Force-time curve data was computed using a custom analysis program for Labview software and filtered using a low pass 4th order Butterworth filter sampling at 1,000 hz. Intra-class correlation coefficients (Table 1) and coefficient of variation (Table 2) were calculated to determine intra-set reliability and relative measurement error using both 3-repetition and 2-repetition means for each set. For 2-repetition means, the two closest values from each set were averaged for each of the six variables. A 2x8 repeated measures analysis of variance was used to determine main effects and interactions for condition and load. Cohen's-*d* effect sizes were calculated at each load to examine the magnitude of differences between conditions. Type one error rate was set at 0.05 for all statistical analyses. Version 22 of SPSS statistical analysis software (IBM Co., NY, USA) and Microsoft Excel 2013 (Microsoft, Redmond, WA, version 15.0.4711.1000) was used to perform all statistical analyses.

Table 1 – Average Intraclass Correlation Coefficients

Variable	ICC	95% Confidence Upper Bound	95% Confidence Lower Bound	F Test Value
Peak Force	0.994	.335	.999	1562.331
Peak Power	0.955	-.027	.992	209.870

Peak Velocity	0.997	.641	1.000	2837.540
Impulse	0.953	-.034	.991	155.859
Work	0.999	.992	1.000	1676.450
Vertical Displacement	0.999	.738	1.000	10923.446

Table 2 – Group Mean Coefficient of Variation at Each Load

	High Bar Back Squat						Low Bar Back Squat					
Load	Peak Force	Peak Power	Peak Velocity	Impulse	Concentric Work	Vertical Displacement	Peak Force	Peak Power	Peak Velocity	Impulse	Concentric Work	Vertical Displacement
20%	16.0%	19.3%	14.6%	9.7%	7.8%	7.4%	14.0%	17.9%	13.1%	14.9%	10.6%	2.7%
30%	12.6%	14.4%	12.8%	7.7%	6.9%	6.1%	12.9%	15.4%	11.1%	11.4%	11.1%	2.3%
40%	10.3%	12.0%	11.8%	7.8%	6.5%	6.1%	13.9%	15.1%	11.5%	9.7%	11.0%	3.1%
50%	10.6%	15.3%	10.9%	7.9%	6.2%	6.3%	14.4%	18.8%	13.1%	14.6%	10.6%	3.2%
60%	10.5%	11.3%	8.0%	7.8%	4.5%	6.3%	16.3%	14.6%	10.3%	8.5%	12.2%	2.3%
70%	11.2%	13.7%	9.8%	9.6%	4.8%	6.9%	15.0%	14.0%	10.5%	7.1%	10.4%	2.7%
80%	10.9%	13.7%	10.4%	11.0%	7.5%	6.7%	15.6%	21.5%	10.0%	7.3%	10.8%	3.0%
90%	9.5%	20.0%	17.4%	19.3%	6.8%	6.9%	16.0%	14.8%	11.1%	15.1%	10.0%	3.6%

Each repetition was broken into two phases, eccentric and concentric. The eccentric phase started at the moment that vertical displacement decreased and ended at the lowest point of vertical displacement. The concentric phase started at the lowest point of vertical displacement and ended at following peak or plateau in vertical displacement.

RESULTS

Two subjects withdrew from this study during the practice phase due to unrelated lower-limb injury, leaving six to be included in the final analysis. Anthropometric and descriptive data can be found in Table 3. In all statistical comparisons between load and condition, a 2-rep mean was calculated for each variable per set per subject because this yielded slightly higher ICC values and lower CV values than a 3-rep mean in most instances. The raw data were processed using a custom Labview analysis program and 2-repetition means were calculated for each variable at each load for each subject. Group mean data for all loads can be found in Table 4.

Table 3 – Participant Descriptive Data

Participant	Age (years)	Height (m)	Seated Height (m)	Body mass (kg)	HBBS 1RM (kg)	HBBS Stance Width (kg)	LBBS Stance Width (m)	Experience (years)	Squat/Body mass
1	22.5	1.72	0.925	83.5	158	0.34	0.45	8	1.89
2	30.1	1.805	0.965	97.3	149	0.36	0.385	11	1.53
3	26.1	1.76	0.915	88.4	175	0.34	0.41	13	1.98
4	26.5	1.775	0.93	78	150	0.245	0.335	3	1.92
5	22.6	1.77	0.915	95.2	174	0.335	0.355	7	1.83
6	22.1	1.83	0.955	83.1	136	0.34	0.44	3	1.64
mean ± SD	25.0 ± 3.1	1.777 ± 0.038	0.934 ± 0.021	87.6 ± 7.5	157 ± 15.3	0.327 ± 0.041	0.396 ± 0.046	7.5 ± 4.1	1.8 ± 0.18

Table 4 – Group Mean External Kinematic and Kinetic Data (mean ± SD)

Load	Peak Force (N)		Peak Power (W)		Peak Velocity (ms^{-1})	
	HBBS	LBBS	HBBS	LBBS	HBBS	LBBS
20%	2190 ± 54[3]	2121 ± 71[3]	2496 ± 69[3]	2475 ± 33[3]	1.84 ± 0.04[4]	1.79 ± 0.01[4]
30%	2402 ± 34[4]	2332 ± 30[4]	2658 ± 25[4]	2608 ± 50[4]	1.78 ± 0.02[4]	1.72 ± 0.02[4]
40%	2632 ± 32[4]	2573 ± 34[4]	2748 ± 36[4]	2678 ± 56[4]	1.64 ± 0.02[4]	1.61 ± 0.02[4]
50%	2867 ± 39[4]	2720 ± 22[4]	2862 ± 32[4]	2796 ± 27[4]	1.52 ± 0.01[4]	1.46 ± 0.01[4]
60%	2931 ± 29[4]	2776 ± 45[4]	2815 ± 22[3]	2778 ± 44[3]	1.40 ± 0.01[4]	1.36 ± 0.01[4]
70%	3048 ± 28[4]	2968 ± 32[4]	2874 ± 56[2]	2913 ± 56[2]	1.31 ± 0.02[3]	1.29 ± 0.02[2]
80%	3146 ± 30[4]	3084 ± 28[4]	2892 ± 29[4]	2811 ± 60[4]	1.21 ± 0.02[4]	1.17 ± 0.02[4]
90%	3176 ± 25[1]	3192 ± 49[1]	2624 ± 57[4]	2473 ± 46[4]	1.05 ± 0.02[4]	0.98 ± 0.02[4]

Load	Impulse (N*s)		Concentric Work (J)		Vertical Displacement (m)	
	HBBS	LBBS	HBBS	LBBS	HBBS	LBBS
20%	745 ± 11.3[3]	737.3 ± 4.3[3]	809.6 ± 9.8[3]	798.1 ± 8.2[3]	0.687 ± 0.006[4]	0.672 ± 0.008[4]
30%	861.1 ± 7.2[3]	870 ± 8.3[3]	907.1 ± 10.4	906.3 ± 3.4	0.689 ± 0.005[4]	0.667 ± 0.003[4]
40%	1014.3 ± 9.6[4]	1028.1 ± 6.8[4]	1028.3 ± 14.1[4]	1006.6 ± 5.6[4]	0.679 ± 0.004[4]	0.66 ± 0.004[4]
50%	1224.3 ± 13.2[4]	1276.5 ± 4.9[4]	1132.2 ± 9	1132.7 ± 12.7	0.679 ± 0.005[4]	0.66 ± 0.003[4]
60%	1460.6 ± 16.9[4]	1490.5 ± 10.5[4]	1224.2 ± 11.9[4]	1201.5 ± 8.4[4]	0.67 ± 0.004[4]	0.65 ± 0.003[4]
70%	1809.1 ± 13.7[2]	1820 ± 21.1[2]	1336.2 ± 12.4[3]	1323.8 ± 14.9[3]	0.671 ± 0.003[4]	0.648 ± 0.004
80%	2212.4 ± 34.3[4]	2268.3 ± 34.5[4]	1420.5 ± 6.5[4]	1406.6 ± 13.3[4]	0.659 ± 0.003[4]	0.648 ± 0.002[4]
90%	2856.1 ± 91.1[4]	3032.1 ± 73.4[4]	1509.5 ± 12.6[3]	1495.8 ± 10.9[3]	0.658 ± 0.003[4]	0.649 ± 0.003[4]

[1] *small Cohen's-d effect size between conditions (d>0.20)*

[2] *medium Cohen's-d effect size between conditions (d>0.50)*

[3] *large Cohen's-d effect size between conditions (d>0.80)*

[4] *very large Cohen's-d effect size between conditions (d>1.30)*

Table 5 – Results of Two-Way Repeated Measures Analysis of Variance for Selected Variables

	Condition			**Load**			**Style*Load**		
	df	**F**	**p**	**df**	**F**	**p**	**df**	**F**	**p**
Peak Force	1.00	0.73	0.433	7.00	42.65	0.000*	7.00	0.96	0.479
Peak Power	1.00	0.72	0.434	7.00	4.35	0.001*	7.00	0.38	0.907
Peak Velocity	1.00	2.08	0.209	7.00	76.59	0.000*	7.00	0.17	0.989
Impulse	1.00	1.39	0.292	7.00	130.64	0.000*	7.00	1.04	0.421
Concentric Work	1.00	0.11	0.753	7.00	355.91	0.000*	7.00	0.27	0.961
Vertical Displacement	1.00	1.05	0.352	7.00	10.84	0.000*	7.00	0.56	0.783

Note: Alpha level was set to $p < 0.05$

**indicates significance at the* $p = 0.05$ *level*

No significant main effects were found for condition at the $p<0.05$ level in any of the six reported variables (Table 5). There was a significant load effect for all six variables. No significant interaction effects were found at the $p<0.05$ for any of the six variables. Trend analysis was performed and each variable fitted with a polynomial based on both observed power and visual analysis of the load effect plot: peak force, 1st order; peak power, 2nd order; and peak velocity, 1st order; impulse, 2nd order; work, 1st order; and vertical displacement, 1st order (Figures 1–6).

The HBBS condition showed a trend towards greater peak forces, peak power, and peak velocities across the majority of the loading spectrum, while the LBBS generated higher peak force at the 90% load and higher peak power at the 70% load (Table 4). Larger vertical displacement and work values were recorded for the HBBS condition at all loads, especially loads 30%–70% for vertical displacement. The LBBS generated a larger impulse at each load except 20%. Small to very large effect sizes were found between HBBS and LBBS at various loads in all six variables.

Figure 1 – Changes in Peak Force with Increasing Load

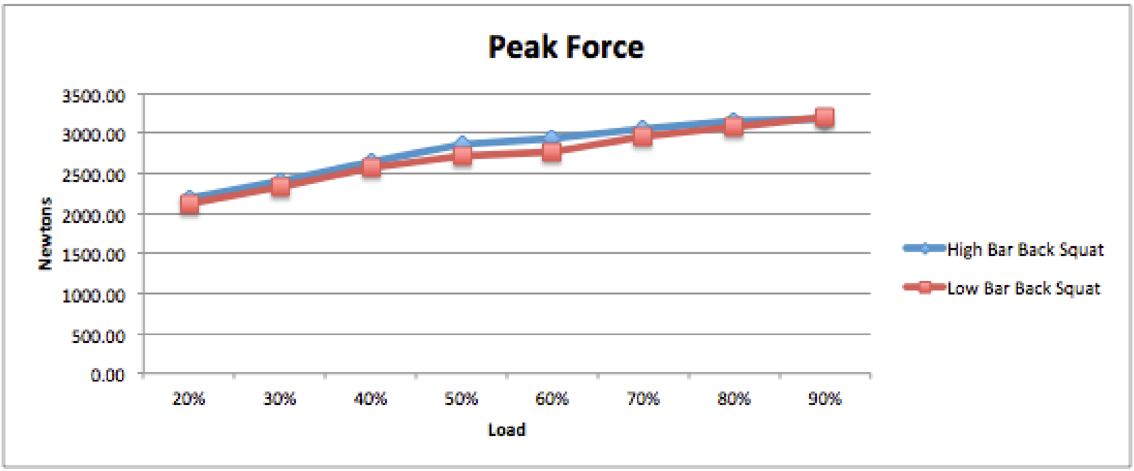


Figure 2 – Changes in Peak Power with Increasing Load

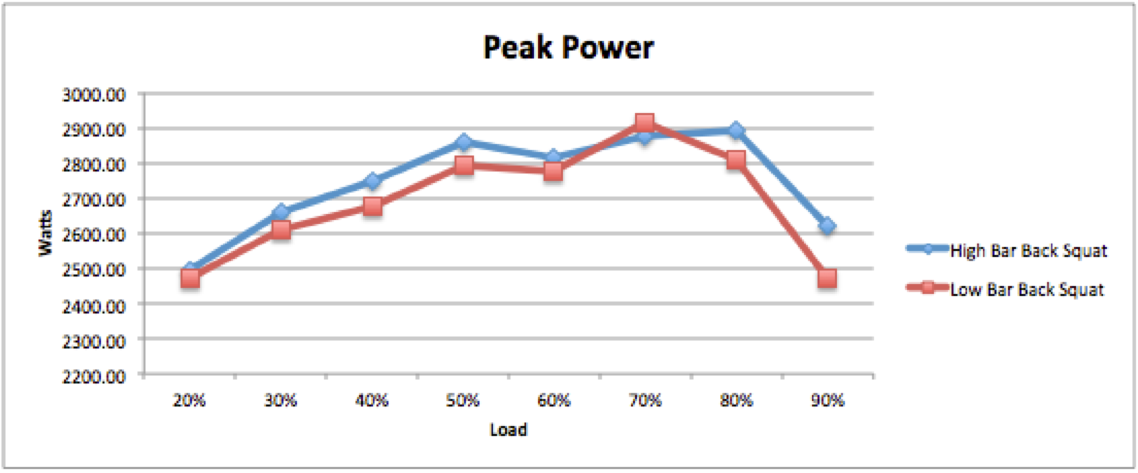


Figure 3 – Changes in Peak Velocity with Increasing Load

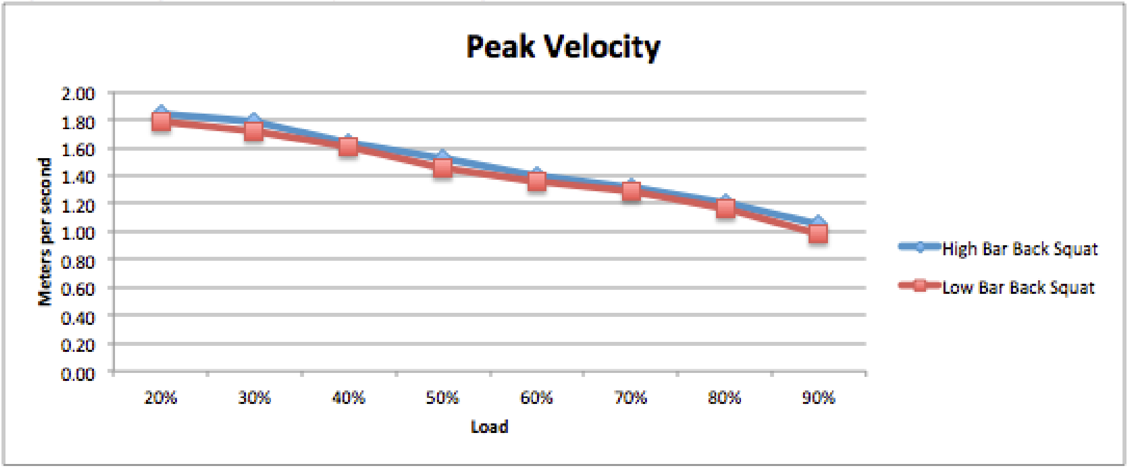


Figure 4 – Changes in Impulse with Increasing Load

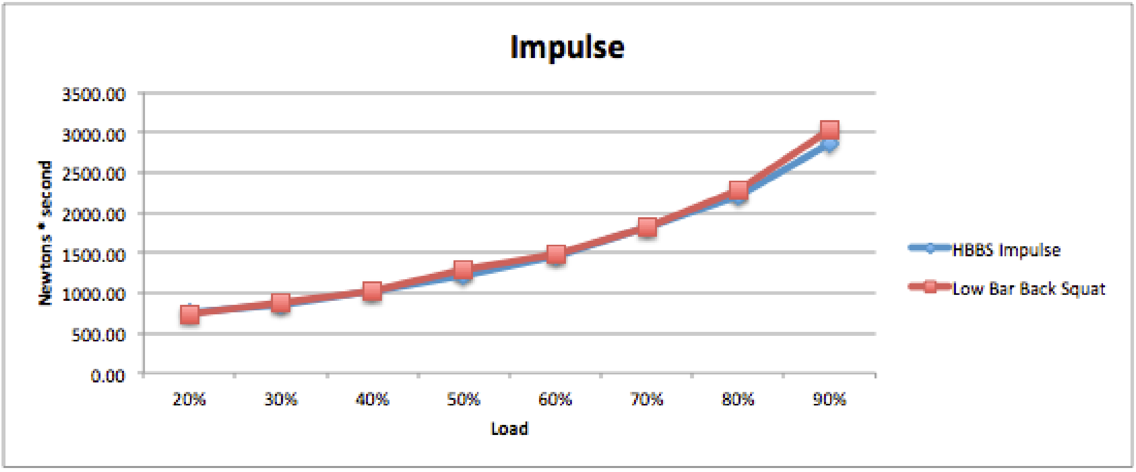


Figure 5 – Changes in Work with Increasing Load

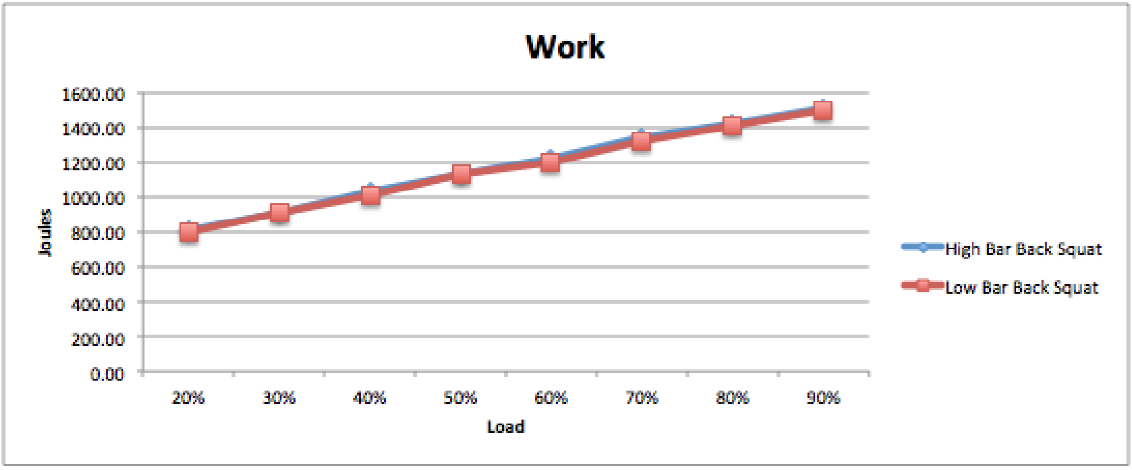
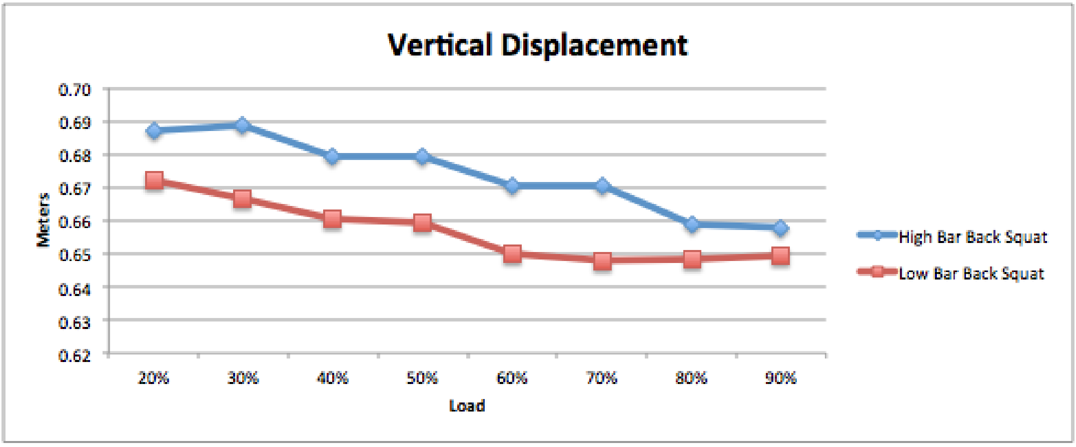


Figure 6 – Changes in Vertical Displacement with Increasing Load



DISCUSSION

The results of this study revealed a trend towards small external kinematic and kinetic differences between the HBBS and LBBS at a variety of loads. Statistical analysis did not uncover significant differences between conditions across the loading spectrum or at specific loads, but when all data points are considered simultaneously, several practically significant trends arise.

The only statistically significant findings in the present study were the effect of load on the kinetic and kinematic variables tested. Visual as well as statistical analysis of the load main effects shows that both conditions behave in a similar manner as load increases. The load effect trends for peak force, peak power, and peak velocity have been detailed previously in investigations of the force-velocity curve during squatting movements (13, 51, 76). An anomaly present in the current dataset is that in both squat conditions peak force and peak power decrease sharply from 50% to 60% before increasing again to 70%, creating a dip in the middle of what would otherwise be a parabolic curve. Statistically speaking, a 5th order polynomial best fit the peak force–load plot instead of the more parabolic shaped quadratic function or linear function that might be expected. This may have been due to 1) an increase in allotted rest after the 50% load or 2) a small sample size that responds dramatically to individual outlying data. In the first case, the longer rest (increasing from 2 minutes to 3-4 minutes) may have led to a slight “cooling down” effect and subsequent inhibition of motor-units, decreased excitation of neural pathways, or loss of focus by the subject on maximal movement intent despite verbal encouragement. In the second case, the data were processed using a 2-repetition average to improve intra-set reliability, but with only 6 subjects, a single data point can still pull the mean downward. This dip at 60% could be a combination of both factors. However, its presence in both conditions suggests that perhaps the longer rest factor was the primary cause.

Peak power was maximized at 80% load in the HBBS and 70% in the LBBS. These figures are higher than previous data by Cormie, McCaulley, Triplett and McBride (14) that reported peak power was maximized at 50% of 1 repetition maximum in Division I college strength and power athletes and by Izquierdo, Hakkinen, Gonzalez-Badillo, Ibanez and Gorostiaga (32) that power was maximized at 60% in cricket and handball players. Given the aforementioned possibility of an outlying data point at 60% load in both conditions, and given the parabolic nature of the peak power–load curves, it is plausible that given a larger sample size peak power may have been maximized at 60% load in both conditions.

Both conditions exhibited similar impulse-load trends, fitted with a linear polynomial with an observed power of 1.00 or a quadratic polynomial with an observed power of 0.99 Visual observation of the impulse-load graph (Figure 1) seems to suggest that impulse changes in a quadratic fashion with increases in load, especially for the LBBS, which had a higher impulse at loads 30%-90% but most significantly at 90% (5.8% higher than the HBBS).

The work performed at each load increased linearly in both conditions, and statistical trend analysis fitted the work–load trend with a linear polynomial with an observed power of 1.00. This makes mathematical sense, as work is the product of displacement and force and force increased linearly as displacement remained the same aside from the statistically small changes discussed in the following paragraph.

It is interesting that weight-trained males with many years of squatting experience exhibited a trend towards a decrease in vertical displacement (i.e. squatting depth) as load increased. While some research has focused on differences between squats to various predetermined depths (7, 11, 74), to the author’s knowledge no investigation has reported a change in self-selected squat depth during the HBBS or LBBS as load increases. For this study each subject was told to squat “as low as effectively possible while maintaining form” for each condition, yet vertical displacement decreased by 2.9 cm (4.2%) in the HBBS and 2.3 cm (3.4%) in the LBBS from 20% to 90%. Wretenberg, Feng and Arborelius (74) reported larger hip and knee moments in deep squats versus squats to parallel, and thus a decrease in squat depth at heavier loads may be a subconscious attempt to spare excessive joint forces. It could be that subjects decreased squatting depth in anticipation of maximal concentric movement intent resulting in an early upward drive to overcome the heavier loads. This is plausible, given that Escamilla, Fleisig, Zheng, Lander, Barrentine, Andrews, Bergemann and Moorman (20) observed that peak knee extensor activity occurs at 90 degrees of knee flexion during squats. Squatting to a shallower depth would not only maximize muscle activation and improve mechanical advantage, but lower the overall work performed with each rep. It is important to note that this trend of decreasing displacement with increasing load was observed in both group and individual data from both conditions, and thus is unlikely to have occurred due to outlying data. A final component that may have effected displacement was fatigue. Although subjects were given complete rest, it is the nature of a multiple set protocol that some amount of fatigue is carried into each subsequent set. Fatigue coupled with increases in muscular demand due to increasing load likely played a role.

The HBBS displayed a trend towards larger values than the LBBS in 22 out of 24 data points between peak force, peak power, and peak velocity (three variables at eight loads each), with 21 of those differences having large to very large effect sizes (see Table 2). This agrees with data from Swinton, Lloyd, Keogh, Agouris and Stewart (70), who found that peak power and peak velocity were higher in the HBBS than the LBBS at each of the three loads they measured (30%, 50%, and 70% of 1 repetition maximum) and that peak force was higher in two of the loads (30% and 50% of 1 repetition maximum). The authors declined to comment further on the practical significance of these findings due to a lack of statistical significance, however the agreement between the two datasets points to a possible hypothesis that has existed previously among sport scientists (Stone, personal communication, 2015) but now has preliminary supporting evidence: that despite anecdotal evidence supporting higher 1 repetition maximums using the LBBS, at submaximal loads the HBBS may have a greater capacity to produce peak force, peak power, and peak velocity.

There was a trend towards greater impulse in the LBBS than the HBBS at loads 30%-90% despite the trends toward peak force being higher in the HBBS at these same loads. It may have taken subjects longer to complete each repetition of the LBBS condition because of these lower velocity values in the LBBS, thus leading to more time during which to generate a high impulse. Also important to consider is mean force, which was not calculated, may have been higher in the LBBS, leading to a greater impulse. This could also be a mechanism by which trainees are able to purportedly lift greater loads because it may reduce or negate the mechanically disadvantageous sticking region that is responsible for failed lifts. A reduced sticking region in the LBBS would mean that the athlete is able to generate relatively high forces for a larger duration of the concentric phase than in the HBBS. Thus a larger impulse may be one characteristic of the LBBS that is advantageous to lifting maximal loads, a line of reasoning that is bolstered by the aforementioned magnitude of difference between the LBBS and HBBS at the 90% load. It is possible that as the load approaches 100% that the magnitude of difference would continue to increase.

There was a trend towards HBBS vertical displacement being 1.3% to 3.5% greater than in the LBBS, which translates to between 0.9 cm and 2.3 cm. These data confirm that of

Escamilla (17), who reported that powerlifters employing a narrow stance (similar to the HBBS) had greater vertical displacement than powerlifters with medium and wide stances. A larger vertical displacement also affords more range of motion through which to accelerate concentrically, possibly contributing to the trend of higher peak velocities and peak powers observed in the HBBS condition.

Although the HBBS displayed a trend towards larger values across many loads for peak force, peak power, peak velocity, work, and impulse, the magnitude of these differences in the current study is small and confined to this specific population. Furthermore, due to a small sample size (n=6), the observed power in each of these between-condition comparisons remains statistically low (0.059–0.218). It remains to be seen whether these trends exist in larger populations of trained individuals and athletes and whether the findings can be extrapolated to more diverse subpopulations of athletes. Further research should seek to replicate these findings in larger populations of well-trained subjects. Furthermore, researchers should investigate between-condition differences in average rate of force development and rate of force development at performance-critical time points. This can be achieved using the present study's research design but employing a larger and more homogenous population to improve statistical power and lower measures of error. There are limitations to using cross-sectional investigations alone to inform decisions about what are inherently long-term deterministic aspects of the training process. Ultimately, longitudinal controlled intervention studies comparing the efficacy of the HBBS to the LBBS will yield the most insight into these exercises' external kinetic and kinematic differences and ultimately their uses in specific athletic populations. Correlational studies can also be utilized to compare tested HBBS and LBBS 1 repetition maximums and isometric HBBS and LBBS characteristics to previously established tests of athleticism such as the vertical static and countermovement jumps, sprint times, and isometric mid-thigh pull (9, 37, 65, 66).

Based on the data of Swinton, Lloyd, Keogh, Agouris and Stewart (70) and on the trends found in this study, it is hypothesized that the HBBS will generate higher peak force, peak power, peak velocity, vertical displacement, and work values at submaximal loads, but that the LBBS will generate larger impulse values and that the magnitude of this difference will increase as load increases, especially above 80%. If the LBBS technique does in fact aid in the lifting of maximal loads (as claimed by powerlifters), it would seem when testing the two conditions at the same absolute load that the LBBS would generate the higher numbers, since the subject would be using a lower relative percentage of his LBBS 1 repetition maximum than HBBS 1 repetition maximum. From anecdotal observations it is evident that during vertical jump or squat jump tests athletes almost never self-select stance-widths as wide as those found in the LBBS, instead opting for a width closer to shoulder width, similar to the traditional HBBS stance. In a back squat this close stance position puts greater stress on the knee extensors (18, 74) due to forward translation of the knees (24) which, coupled with an upright torso is similar to that found in a vertical jump (18, 40). Since high takeoff velocities are reliable predictors of vertical jump height (22, 28). it may be that this position is advantageous for maximizing peak force, peak power, and peak velocity. Future research comparing the HBBS and LBBS should test the subjects' actual 1 repetition maximum for both conditions so that any differences in relative percentage between conditions can be accounted for.

The authors further hypothesized that the HBBS showed a trend towards higher peak values in force, power, and velocity due to its biomechanical similarities to the vertical jump. If this is true, then the HBBS is more specific to the task of vertical jumping and would thus have a higher transfer of training effect than the LBBS to those sports in which jumping is a primary component (for example basketball, volleyball, and football). This hypothesis would be best suited for the type of longitudinal training intervention study mentioned previously.

Finally, the authors hypothesize that in a longitudinal training intervention study comparing the efficacy of the two conditions in producing favorable strength and power adaptations, that the HBBS group would improve measures of power to a greater extent than the LBBS group. We further hypothesize that, given equal repetitions and training intensities, the HBBS would produce greater gains in cross-sectional area and maximal strength due to the HBBS's trend towards larger work and peak force, peak power, and peak velocity values. Essentially, the authors suspect that during each repetition of the HBBS, a greater amount of work would performed at a higher exercise intensity than the LBBS. Work is measure of volume load, and the power output of a movement defines its exercise intensity (63), and since training at higher intensities and volumes yields greater gains in strength and related characteristics (48, 63, 72), the HBBS group would theoretically experience greater improvements in measures of strength and related characteristics than the LBBS group.

CONCLUSIONS

The findings of this study indicate that the HBBS and LBBS exhibit kinetic and kinematic differences that may be relevant to the athletic population. The HBBS condition tended to generate greater peak force, peak power, peak velocity, work, and displacement values at a variety of absolute loads, while the LBBS tended to generate higher impulse values at those same loads. These statements are supported by the number of data points supporting each trend (eight loads for each variable) and the small–very large effect sizes calculated at every load in each variable.

In conclusion, the between–condition differences found in the current study were not large enough to conclusively determine whether one condition will generate larger values for any of the six external kinetic and kinematic variables outside the population of this study. It is unclear whether the observed differences were due to between condition differences or other factors (outlying data points, individual subject differences, training status of subjects) because of the low statistical power. Since strength and power athletes desire to maximize strength and power related variables, it seems that both the HBBS and LBBS should be considered as primary training exercises for the development of lower body strength and power.

PRACTICAL APPLICATIONS

Specific implementation of these findings in an athlete's annual training plan will depend on the sport demands and training status of the individual. The principle of specificity dictates that a specific exercise will cause a specific response (68). The combined responses to each individual training stimulus that form a specific training protocol will drive a specific adaptation. The well-accepted block periodization model of training (31, 42, 44, 50, 64) necessitates that the focus of physiological adaptations shift with each mesosycle in such a way that one mesocycle potentiates the next. Thus an athlete's focus will not always primarily be maximal strength, or power, or endurance, but will change sequentially in an additive way to preserve gains from one mesocycle and bolster the training and gains in the next.

It has been previously stated that training that maximizing training intensity and volume will increase the magnitude of training adaptation. Because the current study showed a trend towards higher measure of intensity (peak force, peak power, and peak velocity) and volume (work, vertical displacement) in the HBBS, the authors recommend that athletes incorporate the HBBS as their primary squat variation and include it as a primary resistance training exercise during all or most of their annual training plan. Most training is performed at submaximal loads, and to date both this study and that of Swinton, Lloyd, Keogh, Agouris and Stewart (70) show trends toward higher peak force, peak velocity, and peak power values at a range of submaximal loads.

There are three conditions under which the authors suggest that the LBBS might be considered as a primary lower body strengthening exercise. The first is early in an athlete's training cycle when increased cross-sectional area is the goal and movement pattern specificity is not a primary concern. During this mesocycle the LBBS may serve as sufficient variation to further drive hypertrophy of lower body musculature while still serving as an effective bilateral, closed kinetic chain exercise. The second condition is when maximal strength is the training goal. Training with maximal loads is necessary to optimally train maximal strength, and thus a squatting style that allows maximal loads to be lifted may be beneficial. The major drawback in both of these situations, however, is that spending short periods of time practicing a similar movement pattern may disrupt an athlete's established HBBS technique or teach them to move in a way that is detrimental to the rest of their training (such as jumping or weightlifting derivatives). Furthermore, if an athlete is "out of practice" with the LBBS, switching to it for a short time may negate the proposed benefits of increased loading due to the specificity of the strength.

The third and perhaps strongest condition for recommending the LBBS to an athlete is during a period of time where minor injury may contraindicate the use of the HBBS. This could be due to an injury such as patellar tendonitis that is aggravated during loaded end range knee flexion. In cases like this, employing a LBBS would transfer some joint stress from the knees to the hips (55, 74) while still providing a training stimulus to the athlete.

The observed trends in this study and previous external kinetic and kinematic data (70) may provide further validation for the use of the HBBS as a lower body strength exercise in a training cycle when enhancing vertical jump performance is important, since takeoff velocity is a reliable predictor of vertical jump height (22) and the HBBS produced larger peak velocities at each load.

Over time, the product of training volume and intensity dictates the magnitude of training-induced adaptations in cross-sectional area and maximal strength (4, 16, 30, 36, 63). Of the six reported variables in this study, peak power most closely relates to the definition of exercise intensity put forward by Stone, Plisk, Stone, Schilling, O'Bryant and Pierce (63), and work is a measure of exercise volume. It may be that the HBBS is superior in producing these qualities due to the greater volume and intensity that it produces across the loading spectrum. If an athlete can work at the same relative intensity and set and rep scheme but produce higher peak force, peak power, and peak velocity with larger displacement and more work completed, adaptations in strength and power will be greater. The current data suggests that the HBBS allows an athlete to train at the same absolute intensity and set and rep scheme as the LBBS but produce higher peak force, peak power, and peak velocity with larger displacement and more work completed. This larger stimulus, over time, may lead to greater adaptations in cross-sectional area, strength, and explosiveness.

Despite its statistical shortcomings, the trends present in the current study in conjunction with previous research leads the authors to recommend that athletes seeking to increase lower body strength and power adopt the HBBS as a primary resistance training exercise due to the trends towards larger peak force, peak power, peak velocity, and vertical displacement in resistance trained males. If enhancing force, power, or velocity production is a primary goal for an athlete, the squatting style that best maximizes these qualities should be used. This data suggests that the HBBS might be superior to the LBBS in maximizing these qualities, and thus should be considered as a primary exercise for these athletes.

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CHAPTER 4

CONCLUSION

The HBBS and LBBS are incorporated in the resistance training programs of many athletes with the primary goal to enhance maximal strength and power. However, before this study no data existed had examined differences in the two conditions' response to increases in load or differences between conditions at a wide spectrum of loads. Therefore, the purpose of this study was to expand upon the paucity of research surrounding the HBBS and LBBS in order to more fully elucidate the variable–load relationships.

The HBBS condition tended to generate greater peak force, peak power, peak velocity, work, and displacement values at a variety of absolute loads, while the LBBS tended to generate higher impulse values at those same loads. These statements are supported by the number of data points supporting each trend (eight loads for each variable) and the small–very large effect sizes calculated at every load in each variable.

Practical Application to Sport

Specific implementation of these findings in an athlete's annual training plan will depend on the sport demands and training status of the individual. The principle of specificity dictates that a specific exercise will cause a specific response (Stone et al., 2007). The combined responses to each individual training stimulus that form a specific training protocol will drive a specific adaptation. The well-accepted block periodization model of training (Issurin, 2008; Matveyev, 1966; Monteiro et al., 2009; Plisk & Stone, 2003; Stone, Potteiger, et al., 2000) necessitates that the focus of physiological adaptations shift with each mesosycle in such a way that one mesocycle potentiates the next. Thus an athlete's focus will not always primarily be maximal strength, or power, or endurance, but will change sequentially in an additive way to preserve gains from one mesocycle and bolster the training and gains in the next.

It has been previously stated that training that maximizing training intensity and volume will increase the magnitude of training adaptation. Because the current study showed a trend towards higher measure of intensity (peak force, peak power, and peak velocity) and volume (work, vertical displacement) in the HBBS, the authors recommend that athletes incorporate the HBBS as their primary squat variation and include it as a primary resistance training exercise during all or most of their annual training plan. Most training is performed at submaximal loads, and to date both this study and that of Swinton et al. (2012) show trends toward higher peak force, peak velocity, and peak power values at a range of submaximal loads.

There are three conditions under which the authors suggest that the LBBS might be considered as a primary lower body strengthening exercise. The first is early in an athlete's training cycle when increased cross-sectional area is the goal and movement pattern specificity is not a primary concern. During this mesocycle the LBBS may serve as sufficient variation to further drive hypertrophy of lower body musculature while still serving as an effective bilateral, closed kinetic chain exercise. The second condition is when maximal strength is the training goal. Training with maximal loads is necessary to optimally train maximal strength, and thus a squatting style that allows maximal loads to be lifted may be beneficial. The major drawback in both of these situations, however, is that spending short periods of time practicing a similar movement pattern may disrupt an athlete's established HBBS technique or teach them to move in a way that is detrimental to the rest of their training (such as jumping or weightlifting derivatives). Furthermore, if an athlete is "out of practice" with the LBBS, switching to it for a short time may negate the proposed benefits of increased loading due to the task specificity of strength.

The third and perhaps strongest condition for recommending the LBBS to an athlete is during a period of time where minor injury may contraindicate the use of the HBBS. This could be due to an injury such as patellar tendonitis that is aggravated during loaded end range knee flexion. In cases like this, employing a LBBS would transfer some joint stress from the knees to the hips (Schoenfeld, 2010; Wretenberg et al., 1996) while still providing a training stimulus to the athlete.

The observed trends in this study and previous external kinetic and kinematic data (Swinton et al., 2012) may provide further validation for the use of the HBBS as a lower body strength exercise in a training cycle when enhancing vertical jump performance is important, since takeoff velocity is a reliable predictor of vertical jump height (Feltner et al., 2004) and the HBBS produced larger peak velocities at each load.

Over time, the product of training volume and intensity dictates the magnitude of training-induced adaptations in cross-sectional area and maximal strength (Behm, 1995; Dudley et al., 1991; Hather et al., 1991; Kramer et al., 1997; Stone et al., 1998). Of the six reported variables in this study, peak power most closely relates to the definition of exercise intensity put forward by Stone et al. (1998), and work is a measure of exercise volume. It may be that the HBBS is superior in producing these qualities due to the greater volume and intensity that it produces across the loading spectrum. If an athlete can work at the same relative intensity and set and rep scheme but produce higher peak force, peak power, and peak velocity with larger displacement and more work completed, adaptations in strength and power will be greater. The current data suggests that the HBBS allows an athlete to train at the same absolute intensity and set and rep scheme as the LBBS but produce higher peak force, peak power, and peak velocity with larger displacement and more work completed. This larger stimulus, over time, may lead to greater adaptations in cross-sectional area, strength, and explosiveness.

Despite its statistical shortcomings, the trends present in the current study in conjunction with previous research leads the authors to recommend that athletes seeking to increase lower body strength and power adopt the HBBS as a primary resistance training exercise due to the trends towards larger peak force, peak power, peak velocity, and vertical displacement in resistance trained males. If enhancing force, power, or velocity production is a primary goal for an athlete, the squatting style that best maximizes these qualities should be used. This data suggests that the HBBS might be superior to the LBBS in maximizing these qualities, and thus should be considered as a primary exercise for these athletes.

Hypotheses Generated

Based on the data of Swinton et al. (2012) and on the trends found in this study, it is hypothesized that the HBBS will generate higher peak force, peak power, peak velocity, vertical displacement, and work values at submaximal loads, but that the LBBS will generate larger impulse values and that the magnitude of this difference will increase as load increases, especially above 80%. If the LBBS technique does in fact aid in the lifting of maximal loads (as claimed by powerlifters), it would seem when testing the two conditions at the same absolute load that the LBBS would generate the higher numbers, since the subject would be using a lower relative percentage of his LBBS 1 repetition maximum than HBBS 1 repetition maximum. From anecdotal observations it is evident that during vertical jump or squat jump tests athletes almost never self-select stance-widths as wide as those found in the LBBS, instead opting for a width closer to shoulder width, similar to the traditional HBBS stance. In a back squat this closed stance position puts greater stress on the knee extensors (Escamilla, Fleisig, Lowry, et al., 2001; Wretenberg et al., 1996) due to forward translation of the knees (Fry et al., 2003) which, coupled with an upright torso is indeed similar to that found in a vertical jump (Escamilla, Fleisig, Lowry, et al., 2001; MacKenzie et al., 2014) and may be a position more advantageous to maximizing peak force, peak power, and peak velocity since it has been previously shown that high takeoff velocities are reliable predictors of vertical jump height (Feltner et al., 2004; Hanson et al., 2007). This would explain why in the current study the HBBS generated higher peak force, peak power, and peak velocity across the spectrum of loads. Future research comparing the HBBS and LBBS should test the subjects' actual 1 repetition maximum for both conditions so that any differences in relative percentage between conditions can be accounted for.

It is further hypothesized that any differences in adaptation to these two lifts and transfer of training effect into sport lie primarily in their biomechanical components (ie mechanical task specificity) given the low observed power for between–condition effects. As detailed above, it may be that the HBBS is more advantageous to generating peak values in force, power, and velocity due to its biomechanical similarities to the vertical jump. If this is true, then the HBBS is more specific to the task of vertical jumping and would thus have a higher transfer of training effect than the LBBS to those sports in which jumping is a primary component (for example basketball, volleyball, and football). This hypothesis would be best suited for the type of longitudinal training intervention study mentioned previously.

Finally, the authors hypothesize that in a longitudinal training intervention study comparing the efficacy of the two conditions in producing favorable strength and power adaptations, that the HBBS group would improve measures of power to a greater extent than the LBBS group. We further hypothesize that, given equal repetitions and training intensities, the

HBBS would produce greater gains in cross-sectional area and maximal strength due to the HBBS's larger vertical displacement and peak force, peak power, and peak velocity. Essentially, the authors suspect that each repetition of the HBBS, if performed with maximal movement intent, would generate higher peak kinetic and kinematic measures over a larger range of motion than the LBBS. Displacement is a crucial component of volume load and the power output of a movement defines its exercise intensity (Stone et al., 1998), and since training at higher intensities and volumes yields greater gains in strength and related characteristics (Paulsen et al., 2003; Stone et al., 1998; Wernbom et al., 2007), the HBBS group would theoretically experience greater improvements in measures of strength and related characteristics than the LBBS group.

Recommendations for Future Research

It remains to be seen whether these trends exist in larger populations of trained individuals and athletes and whether the findings can be extrapolated to more diverse subpopulations of athletes. Further research should seek to replicate these findings in larger populations of well-trained subjects and in specific populations of athletes. Furthermore, mean concentric rate of force development and rate of force development at critical time points should be investigated for between-condition differences. This could be achieved using the present study's research design but employing a larger and more homogenous population to improve statistical power and lower measures of error. Longitudinal controlled intervention studies comparing the efficacy of the HBBS to the LBBS will yield the most insight into these exercises' external kinetic and kinematic differences and ultimately their uses in specific athletic populations. Correlational studies can also be utilized to compare tested HBBS and LBBS 1 repetition maximums and isometric HBBS and LBBS characteristics to previously established tests of athleticism such as the vertical static and countermovement jumps, sprint times, and isometric mid-thigh pull (Carlock et al., 2004; Kraska et al., 2009; Stone et al., 2003; Stone et al., 2004).

In conclusion, the between–condition differences found in the current study were not large enough to conclusively determine whether one condition will generate larger values for any of the six external kinetic and kinematic variables outside the population of this study. It is unclear whether the observed differences were due to between condition differences or other factors (outlying data points, individual subject differences, training status of subjects) because of the low statistical power. Since strength and power athletes desire to maximize strength and power related variables, it seems that both the HBBS and LBBS should be considered as primary training exercises for the development of lower body strength and power.

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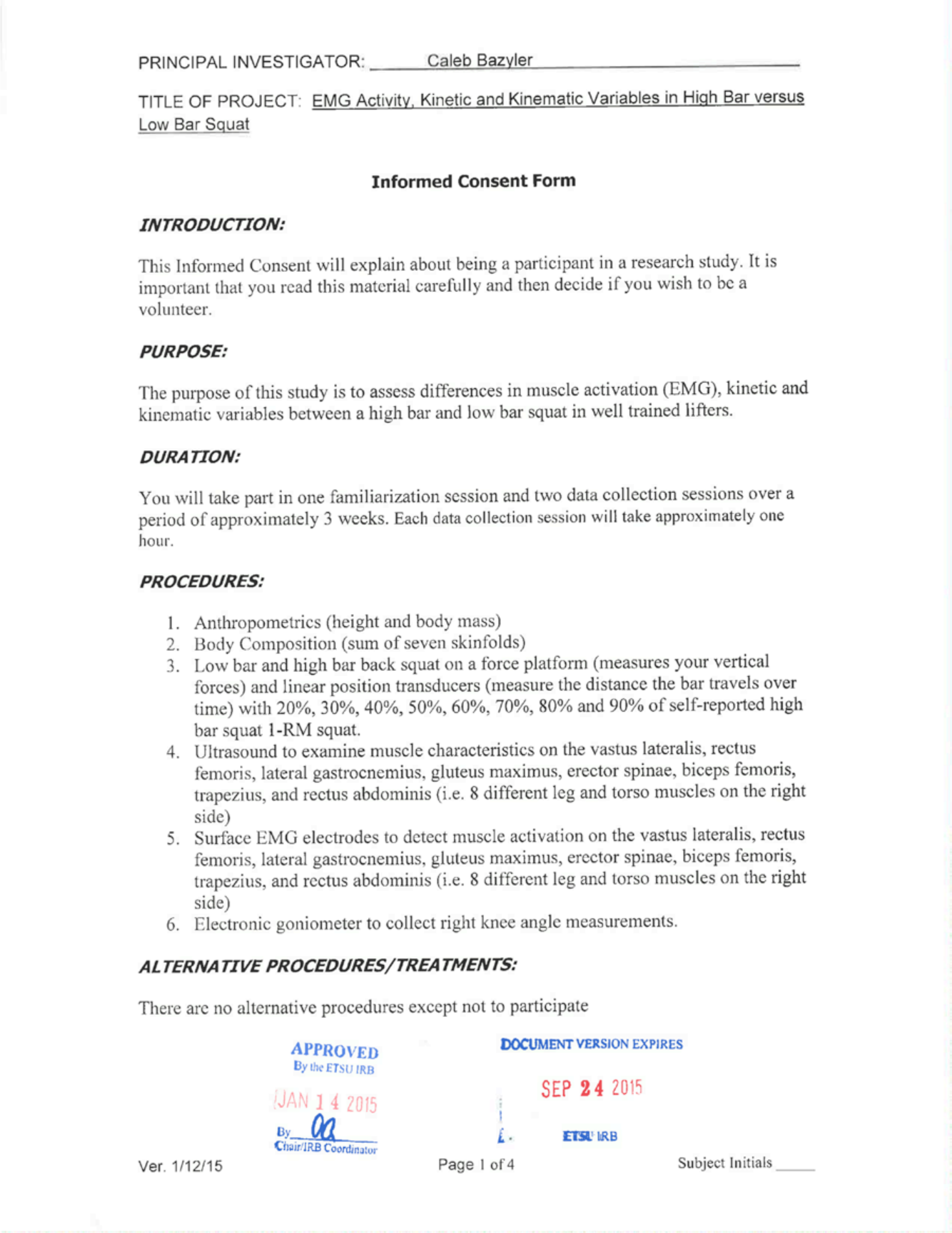
APPENDICES

Appendix A: Informed Consent Documents



PRINCIPAL INVESTIGATOR: Caleb Bazyler

TITLE OF PROJECT: EMG Activity, Kinetic and Kinematic Variables in High Bar versus Low Bar Squat

Informed Consent Form

INTRODUCTION:

This Informed Consent will explain about being a participant in a research study. It is important that you read this material carefully and then decide if you wish to be a volunteer.

PURPOSE:

The purpose of this study is to assess differences in muscle activation (EMG), kinetic and kinematic variables between a high bar and low bar squat in well trained lifters.

DURATION:

You will take part in one familiarization session and two data collection sessions over a period of approximately 3 weeks. Each data collection session will take approximately one hour.

PROCEDURES:

1. Anthropometrics (height and body mass)
2. Body Composition (sum of seven skinfolds)
3. Low bar and high bar back squat on a force platform (measures your vertical forces) and linear position transducers (measure the distance the bar travels over time) with 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% of self-reported high bar squat 1-RM squat.
4. Ultrasound to examine muscle characteristics on the vastus lateralis, rectus femoris, lateral gastrocnemius, gluteus maximus, erector spinae, biceps femoris, trapezius, and rectus abdominis (i.e. 8 different leg and torso muscles on the right side)
5. Surface EMG electrodes to detect muscle activation on the vastus lateralis, rectus femoris, lateral gastrocnemius, gluteus maximus, erector spinae, biceps femoris, trapezius, and rectus abdominis (i.e. 8 different leg and torso muscles on the right side)
6. Electronic goniometer to collect right knee angle measurements.

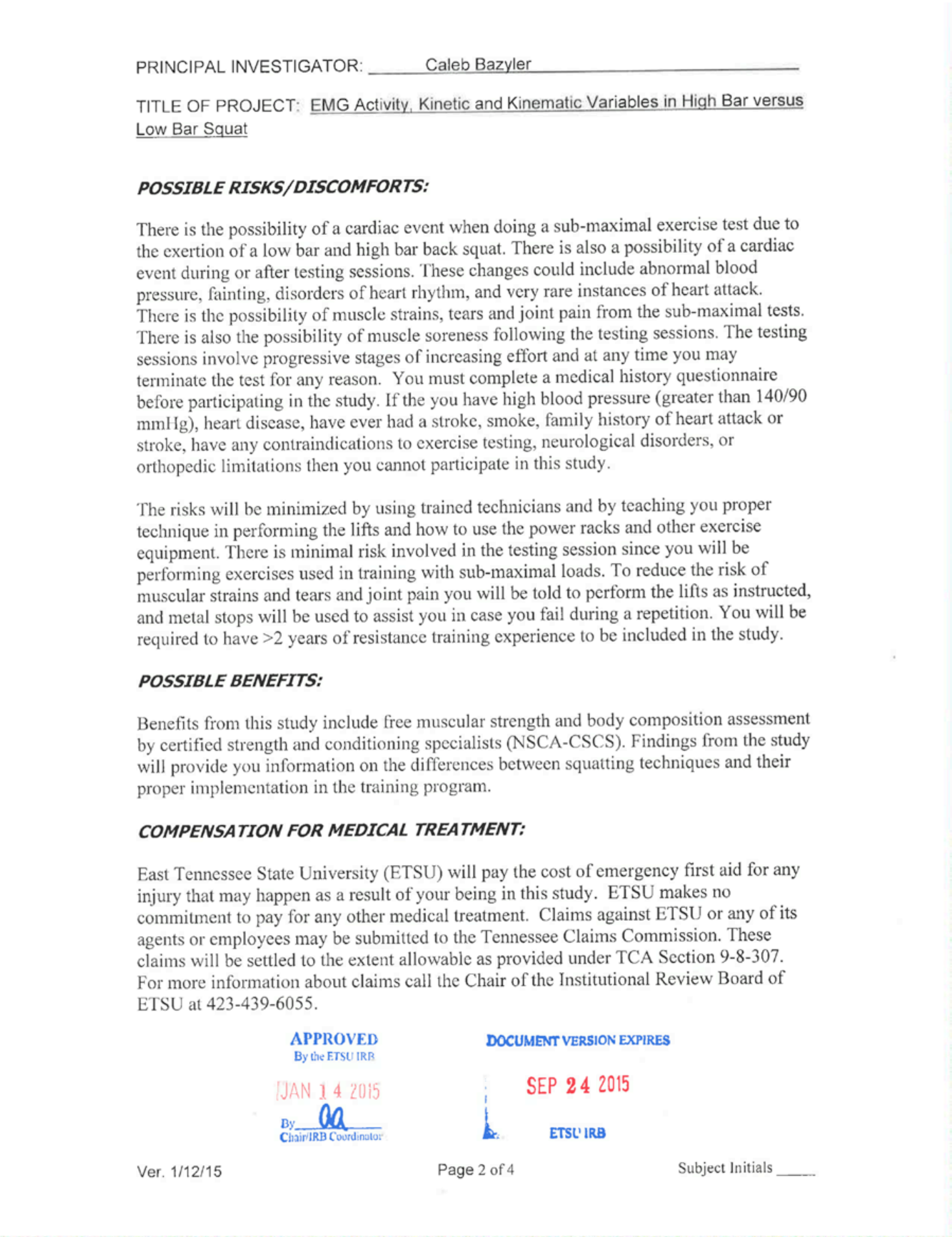
ALTERNATIVE PROCEDURES/TREATMENTS:

There are no alternative procedures except not to participate

APPROVED
By the ETSU IRB
JAN 14 2015
By
Chair/IRB Coordinator

DOCUMENT VERSION EXPIRES
SEP 24 2015
ETSU IRB

Ver. 1/12/15 Page 1 of 4 Subject Initials _____



PRINCIPAL INVESTIGATOR: Caleb Bazyler

TITLE OF PROJECT: EMG Activity, Kinetic and Kinematic Variables in High Bar versus Low Bar Squat

POSSIBLE RISKS/DISCOMFORTS:

There is the possibility of a cardiac event when doing a sub-maximal exercise test due to the exertion of a low bar and high bar back squat. There is also a possibility of a cardiac event during or after testing sessions. These changes could include abnormal blood pressure, fainting, disorders of heart rhythm, and very rare instances of heart attack. There is the possibility of muscle strains, tears and joint pain from the sub-maximal tests. There is also the possibility of muscle soreness following the testing sessions. The testing sessions involve progressive stages of increasing effort and at any time you may terminate the test for any reason. You must complete a medical history questionnaire before participating in the study. If the you have high blood pressure (greater than 140/90 mmHg), heart disease, have ever had a stroke, smoke, family history of heart attack or stroke, have any contraindications to exercise testing, neurological disorders, or orthopedic limitations then you cannot participate in this study.

The risks will be minimized by using trained technicians and by teaching you proper technique in performing the lifts and how to use the power racks and other exercise equipment. There is minimal risk involved in the testing session since you will be performing exercises used in training with sub-maximal loads. To reduce the risk of muscular strains and tears and joint pain you will be told to perform the lifts as instructed, and metal stops will be used to assist you in case you fail during a repetition. You will be required to have >2 years of resistance training experience to be included in the study.

POSSIBLE BENEFITS:

Benefits from this study include free muscular strength and body composition assessment by certified strength and conditioning specialists (NSCA-CSCS). Findings from the study will provide you information on the differences between squatting techniques and their proper implementation in the training program.

COMPENSATION FOR MEDICAL TREATMENT:

East Tennessee State University (ETSU) will pay the cost of emergency first aid for any injury that may happen as a result of your being in this study. ETSU makes no commitment to pay for any other medical treatment. Claims against ETSU or any of its agents or employees may be submitted to the Tennessee Claims Commission. These claims will be settled to the extent allowable as provided under TCA Section 9-8-307. For more information about claims call the Chair of the Institutional Review Board of ETSU at 423-439-6055.

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By the ETSU IRB
JAN 14 2015
By aa
Chair/IRB Coordinator

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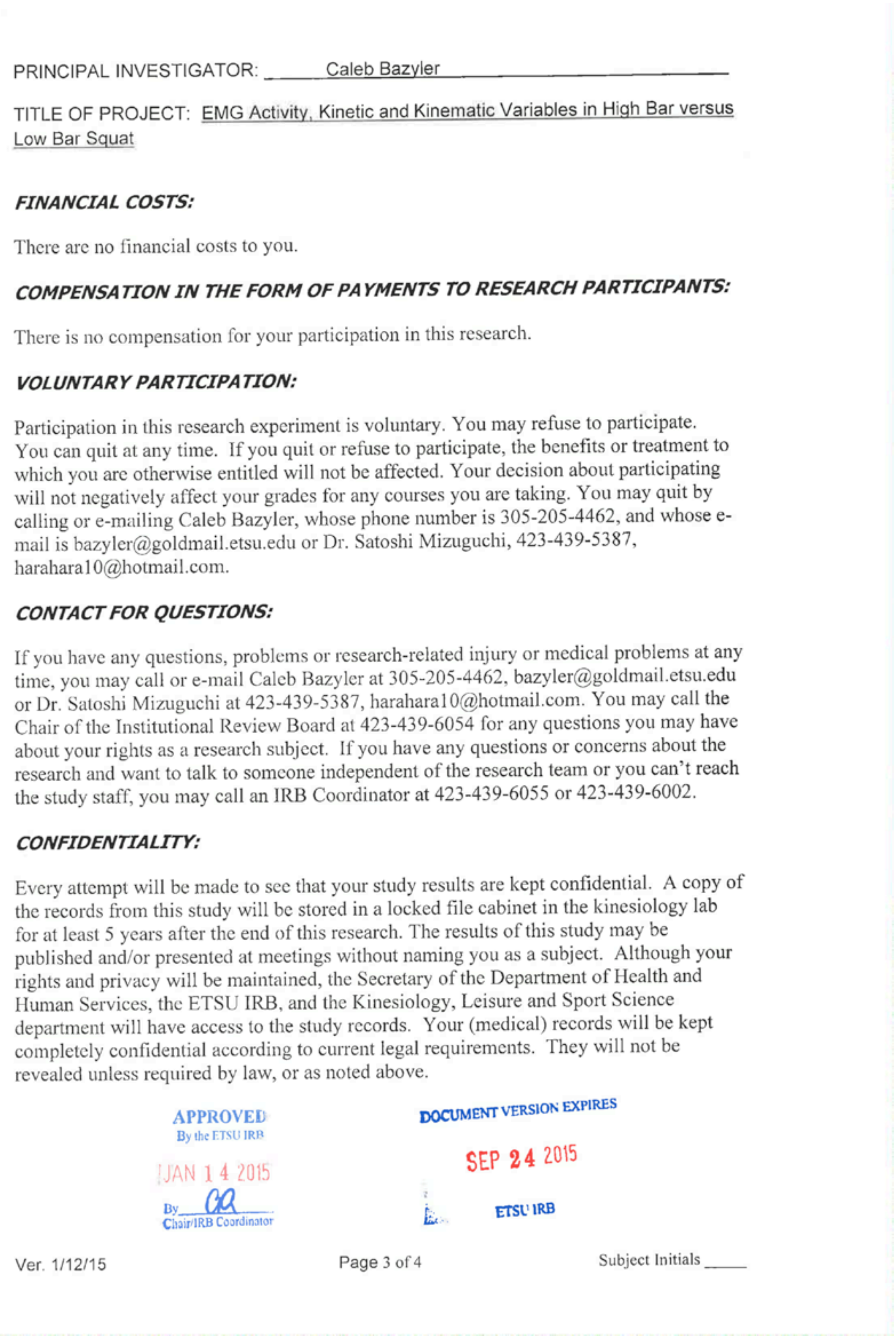

PRINCIPAL INVESTIGATOR: Caleb Bazyler

TITLE OF PROJECT: EMG Activity, Kinetic and Kinematic Variables in High Bar versus Low Bar Squat

FINANCIAL COSTS:

There are no financial costs to you.

COMPENSATION IN THE FORM OF PAYMENTS TO RESEARCH PARTICIPANTS:

There is no compensation for your participation in this research.

VOLUNTARY PARTICIPATION:

Participation in this research experiment is voluntary. You may refuse to participate. You can quit at any time. If you quit or refuse to participate, the benefits or treatment to which you are otherwise entitled will not be affected. Your decision about participating will not negatively affect your grades for any courses you are taking. You may quit by calling or e-mailing Caleb Bazyler, whose phone number is 305-205-4462, and whose e-mail is bazyler@goldmail.etsu.edu or Dr. Satoshi Mizuguchi, 423-439-5387, harahara10@hotmail.com.

CONTACT FOR QUESTIONS:

If you have any questions, problems or research-related injury or medical problems at any time, you may call or e-mail Caleb Bazyler at 305-205-4462, bazyler@goldmail.etsu.edu or Dr. Satoshi Mizuguchi at 423-439-5387, harahara10@hotmail.com. You may call the Chair of the Institutional Review Board at 423-439-6054 for any questions you may have about your rights as a research subject. If you have any questions or concerns about the research and want to talk to someone independent of the research team or you can't reach the study staff, you may call an IRB Coordinator at 423-439-6055 or 423-439-6002.

CONFIDENTIALITY:

Every attempt will be made to see that your study results are kept confidential. A copy of the records from this study will be stored in a locked file cabinet in the kinesiology lab for at least 5 years after the end of this research. The results of this study may be published and/or presented at meetings without naming you as a subject. Although your rights and privacy will be maintained, the Secretary of the Department of Health and Human Services, the ETSU IRB, and the Kinesiology, Leisure and Sport Science department will have access to the study records. Your (medical) records will be kept completely confidential according to current legal requirements. They will not be revealed unless required by law, or as noted above.

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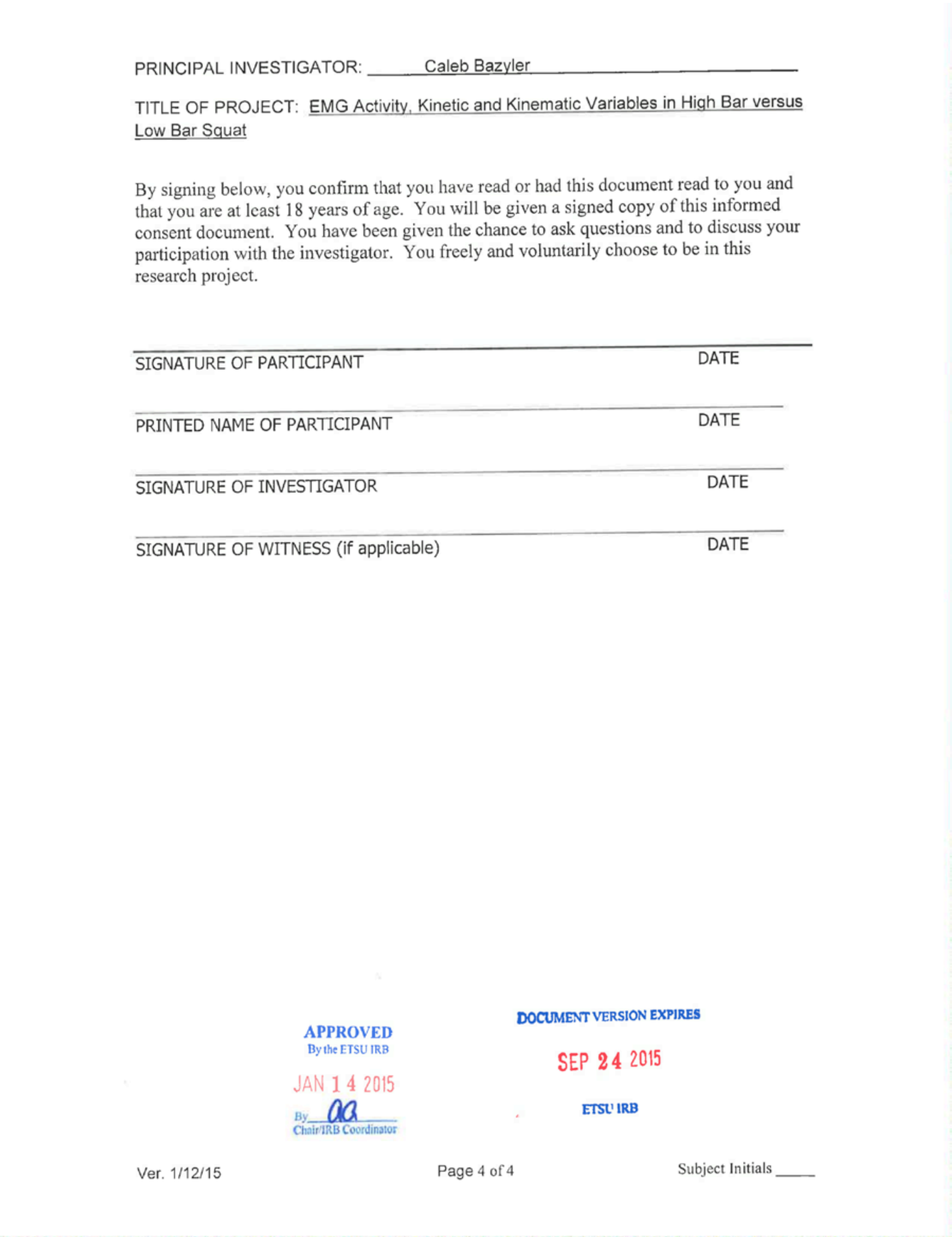
Ver. 1/12/15 Page 3 of 4 Subject Initials _____



PRINCIPAL INVESTIGATOR: Caleb Bazyler

TITLE OF PROJECT: EMG Activity, Kinetic and Kinematic Variables in High Bar versus Low Bar Squat

By signing below, you confirm that you have read or had this document read to you and that you are at least 18 years of age. You will be given a signed copy of this informed consent document. You have been given the chance to ask questions and to discuss your participation with the investigator. You freely and voluntarily choose to be in this research project.

SIGNATURE OF PARTICIPANT	DATE
PRINTED NAME OF PARTICIPANT	DATE
SIGNATURE OF INVESTIGATOR	DATE
SIGNATURE OF WITNESS (if applicable)	DATE

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Subject Initials _____

Appendix B: Health History Questionnaire

Health History Questionnaire

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

Yes/No

2. Do you feel pain in your chest when you do physical exertion?

Yes/No

3. In the past month, have you had chest pain when you were not doing physical activity?

Yes/No

4. Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes/No

5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?

Yes/No

6. Is your doctor currently prescribing drugs (for example, water pills) for a blood pressure or heart condition?

Yes/No

7. Do you know of any other reason why you should not do physical activity?

Yes/No

If yes, please explain:

8. Please list all medications that you are currently taking. Please include vitamins or supplements.

9. Have you been lifting consistently for the past year?

Yes/No

11. Have you ever been diagnosed with any of the health conditions below (check those applicable):

_ heart disease
_ heart surgery
_ high cholesterol
_ diabetes
_ heart attack
_ congenital heart disease
_ high blood pressure
_ stroke
_ premature death

12. Do any of your immediate family/grandparents have a history of (check those applicable):

_ heart disease
_ heart surgery
_ high cholesterol
_ diabetes
_ heart attack
_ congenital heart disease
_ high blood pressure
_ stroke
_ premature death

If yes, please note relationship and age ______________________
____
____

13. Has there been a death in the family via heart attack, heart disease, or stroke?
Yes/No

Appendix C: 4 Week Familiarization Protocol

EMG Activity, Kinetic and Kinematic Variables in High Bar versus Low Bar Squat

Squat Condition Familiarization

Introduction:

Prior to participating in this study, you will perform the following 8 familiarization sessions over the course of 4 weeks to ensure competence with both low bar and high bar squatting techniques. The final work set from each session is to be filmed directly from the side. These files should be uploaded to the Google Drive folder titled with your name before midnight of the same day. At any point during this familiarization period you may choose not to participate in further sessions and be removed from the study without penalty or consequence.

Instructions:

You will complete the following protocol prior to participation in the study. This is to be performed in addition to your current training and at the beginning of a session so that fatigue does not alter motor learning. Please use the same footwear and no belt for both conditions. All percentages are based on most recent beltless high bar squat 1RM or most recent estimated beltless high bar squat 1RM. All reps should be performed in the following manner: a controlled eccentric phase (decent) followed by an explosive concentric phase (ascent). During the concentric phase, move the bar as fast as possible, as if jumping, but do not leave the ground. Pause for 2 seconds between each repetition and after the last repetition before re-racking the bar.

Balanced Familiarization Protocol:

Day 1: HBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%
Day 2: LBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%
Day 3: HBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%, 1x3x70%
Day 4: LBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%, 1x3x70%
Day 5: HBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%, 1x3x70%, 1x3x80%
Day 6: LBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%, 1x3x70%, 1x3x80%
Day 7: HBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%, 1x3x70%, 1x3x80%, 1x3x90%
Day 8: LBS 1x3x20%, 1x3x30%, 1x3x40%, 1x3x50%, 1x3x60%, 1x3x70%, 1x3x80%, 1x3x90%

High Bar Squat (HBS)

Low Bar Squat (LBS)

Video Upload Instructions

Please upload a video of your last set of squats from each session to the study’s shared folder with your name in one of the following ways:

Google Drive

Click on the share link in your email to access the folder, then drag and drop the video file into the folder to upload it.

Email

Send the video file as an attachment to jacobrgoodin@gmail.com

Text

Text the video file to Jacob Goodin at (360) 480-3710

Appendix D: List of Tables and Figures

Table 1 – Average Intraclass Correlation Coefficients

Variable	ICC	95% Confidence Upper Bound	95% Confidence Lower Bound	F Test Value
Peak Force	0.994	.335	.999	1562.331
Peak Power	0.955	-.027	.992	209.870
Peak Velocity	0.997	.641	1.000	2837.540
Impulse	0.953	-.034	.991	155.859
Concentric Work	0.999	.992	1.000	1676.450
Vertical Displacement	0.999	.738	1.000	10923.446

Table 2 – Group Mean Coefficient of Variation at Each Load

	High Bar Back Squat						Low Bar Back Squat					
Load	Peak Force	Peak Power	Peak Velocity	Impulse	Concentric Work	Vertical Displacement	Peak Force	Peak Power	Peak Velocity	Impulse	Concentric Work	Vertical Displacement
20%	16.0%	19.3%	14.6%	9.7%	7.8%	7.4%	14.0%	17.9%	13.1%	14.9%	10.6%	2.7%
30%	12.6%	14.4%	12.8%	7.7%	6.9%	6.1%	12.9%	15.4%	11.1%	11.4%	11.1%	2.3%
40%	10.3%	12.0%	11.8%	7.8%	6.5%	6.1%	13.9%	15.1%	11.5%	9.7%	11.0%	3.1%
50%	10.6%	15.3%	10.9%	7.9%	6.2%	6.3%	14.4%	18.8%	13.1%	14.6%	10.6%	3.2%
60%	10.5%	11.3%	8.0%	7.8%	4.5%	6.3%	16.3%	14.6%	10.3%	8.5%	12.2%	2.3%
70%	11.2%	13.7%	9.8%	9.6%	4.8%	6.9%	15.0%	14.0%	10.5%	7.1%	10.4%	2.7%
80%	10.9%	13.7%	10.4%	11.0%	7.5%	6.7%	15.6%	21.5%	10.0%	7.3%	10.8%	3.0%
90%	9.5%	20.0%	17.4%	19.3%	6.8%	6.9%	16.0%	14.8%	11.1%	15.1%	10.0%	3.6%

Table 3 – Participant Descriptive Data

Participant	**Age (years)**	**Height (m)**	**Seated Height (m)**	**Body mass (kg)**	**HBBS 1RM (kg)**	**HBBS Stance Width (kg)**	**LBBS Stance Width (m)**	**Experience (years)**	**Squat/Body mass**
1	22.5	1.72	0.925	83.5	158	0.34	0.45	8	1.89
2	30.1	1.805	0.965	97.3	149	0.36	0.385	11	1.53
3	26.1	1.76	0.915	88.4	175	0.34	0.41	13	1.98
4	26.5	1.775	0.93	78	150	0.245	0.335	3	1.92
5	22.6	1.77	0.915	95.2	174	0.335	0.355	7	1.83
6	22.1	1.83	0.955	83.1	136	0.34	0.44	3	1.64
mean ± SD	25.0 ± 3.1	1.777 ± 0.038	0.934 ± 0.021	87.6 ± 7.5	157 ± 15.3	0.327 ± 0.041	0.396 ± 0.046	7.5 ± 4.1	1.8 ± 0.18

Table 4 – Group Mean External Kinematic and Kinetic Data (mean ± SD)

Load	Peak Force (N)		Peak Power (W)		Peak Velocity (ms^{-1})	
	HBBS	LBBS	HBBS	LBBS	HBBS	LBBS
20%	2190 ± 54**	2121 ± 71**	2496 ± 69	2475 ± 33	1.84 ± 0.04	1.79 ± 0.01
30%	2402 ± 34***	2332 ± 30***	2658 ± 25	2608 ± 50	1.78 ± 0.02	1.72 ± 0.02
40%	2632 ± 32***	2573 ± 34***	2748 ± 36	2678 ± 56	1.64 ± 0.02	1.61 ± 0.02
50%	2867 ± 39***	2720 ± 22***	2862 ± 32	2796 ± 27	1.52 ± 0.01	1.46 ± 0.01
60%	2931 ± 29***	2776 ± 45***	2815 ± 22	2778 ± 44	1.4 ± 0.01	1.36 ± 0.01
70%	3048 ± 28***	2968 ± 32***	2874 ± 56	2913 ± 56	1.31 ± 0.02	1.29 ± 0.02
80%	3146 ± 30***	3084 ± 28***	2892 ± 29	2811 ± 60	1.21 ± 0.02	1.17 ± 0.02
90%	3176 ± 25	3192 ± 49	2624 ± 57	2473 ± 46	1.05 ± 0.02	0.98 ± 0.02

Load	Impulse (N*s)		Concentric Work (J)		Vertical Displacement (m)	
	HBBS	LBBS	HBBS	LBBS	HBBS	LBBS
20%	745 ± 11.3	737.3 ± 4.3	809.6 ± 9.8	798.1 ± 8.2	0.687 ± 0.006	0.672 ± 0.008
30%	861.1 ± 7.2	870 ± 8.3	907.1 ± 10.4	906.3 ± 3.4	0.689 ± 0.005	0.667 ± 0.003
40%	1014.3 ± 9.6	1028.1 ± 6.8	1028.3 ± 14.1	1006.6 ± 5.6	0.679 ± 0.004	0.66 ± 0.004
50%	1224.3 ± 13.2	1276.5 ± 4.9	1132.2 ± 9	1132.7 ± 12.7	0.679 ± 0.005	0.66 ± 0.003
60%	1460.6 ± 16.9	1490.5 ± 10.5	1224.2 ± 11.9	1201.5 ± 8.4	0.67 ± 0.004	0.65 ± 0.003
70%	1809.1 ± 13.7	1820 ± 21.1	1336.2 ± 12.4	1323.8 ± 14.9	0.671 ± 0.003	0.648 ± 0.004
80%	2212.4 ± 34.3	2268.3 ± 34.5	1420.5 ± 6.5	1406.6 ± 13.3	0.659 ± 0.003	0.648 ± 0.002
90%	2856.1 ± 91.1	3032.1 ± 73.4	1509.5 ± 12.6	1495.8 ± 10.9	0.658 ± 0.003	0.649 ± 0.003

[1] *small Cohen's-d effect size between conditions (d>0.20)*

[2] *medium Cohen's-d effect size between conditions (d>0.50)*

[3] *large Cohen's-d effect size between conditions (d>0.80)*

[4] *very large Cohen's-d effect size between conditions (d>1.30)*

Table 5 – Results of Two-Way Repeated Measures Analysis of Variance for Selected Variables

	Condition			Load			Style*Load		
	df	F	p	df	F	p	df	F	p
Peak Force	1.00	0.73	0.433	7.00	42.65	0.000	7.00	0.96	0.479
Peak Power	1.00	0.72	0.434	7.00	4.35	0.001	7.00	0.38	0.907
Peak Velocity	1.00	2.08	0.209	7.00	76.59	0.000	7.00	0.17	0.989
Impulse	1.00	1.39	0.292	7.00	130.64	0.000	7.00	1.04	0.421
Concentric Work	1.00	0.11	0.753	7.00	355.91	0.000	7.00	0.27	0.961
Vertical Displacement	1.00	1.05	0.352	7.00	10.84	0.000	7.00	0.56	0.783

Note: Alpha level was set to $p < 0.05$

Figure 1 – Changes in Peak Force with Increasing Load

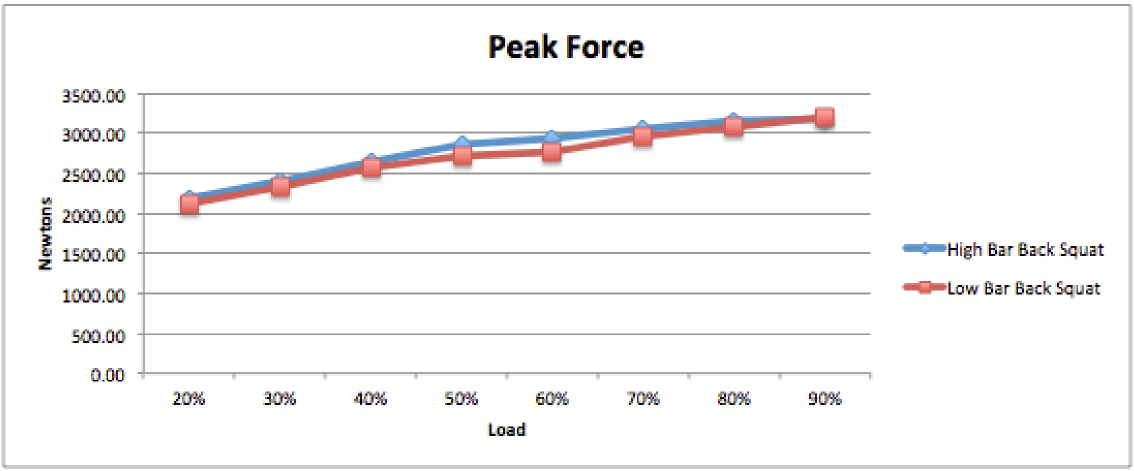


Figure 2 – Changes in Peak Power with Increasing Load

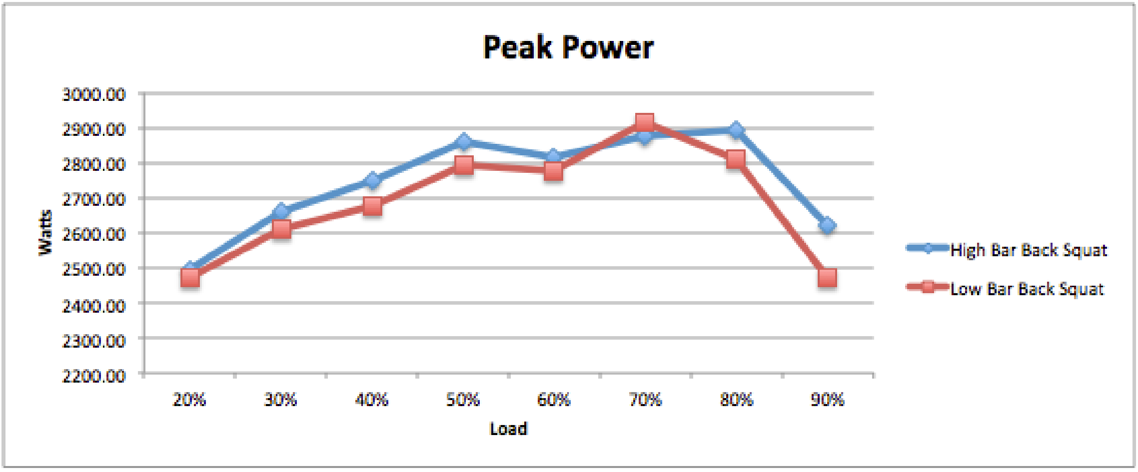


Figure 3 – Changes in Peak Velocity with Increasing Load

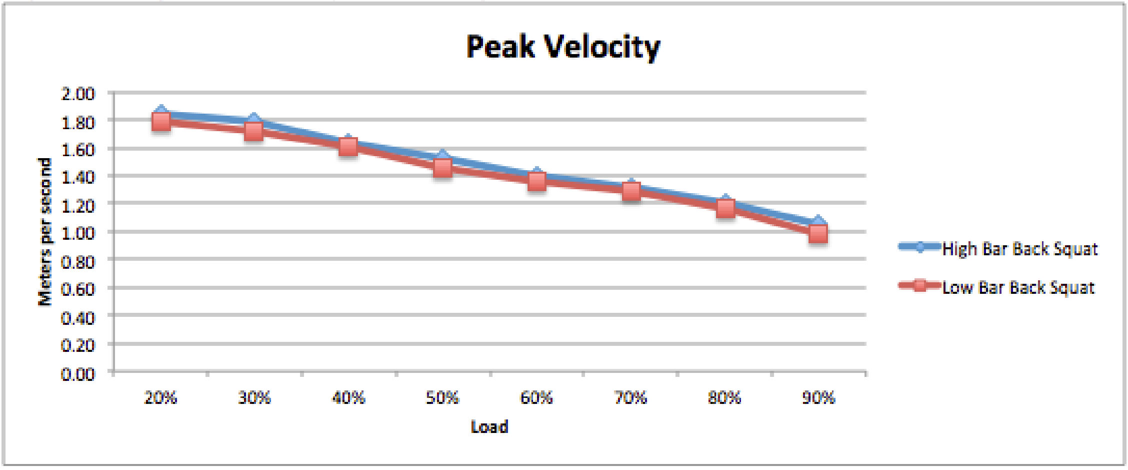


Figure 4 – Changes in Impulse with Increasing Load

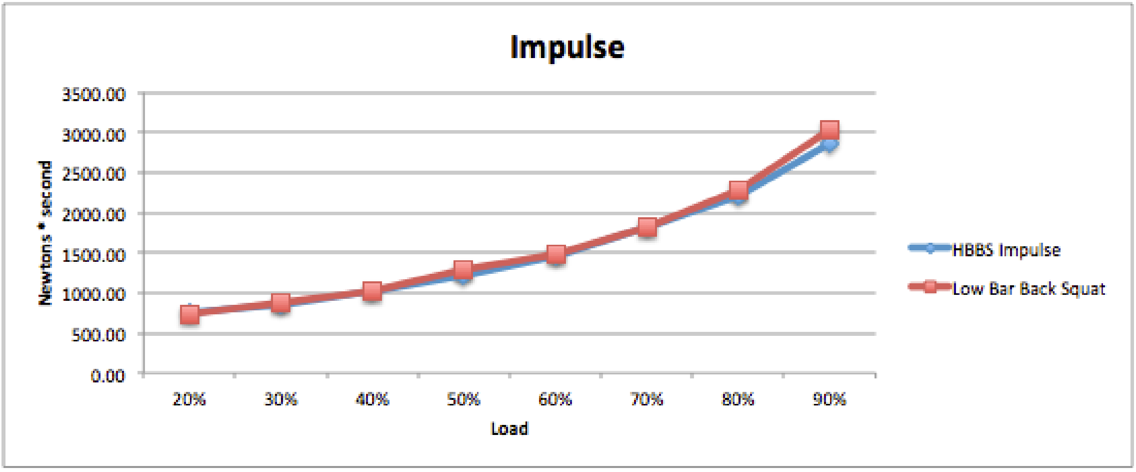


Figure 5 – Changes in Work with Increasing Load

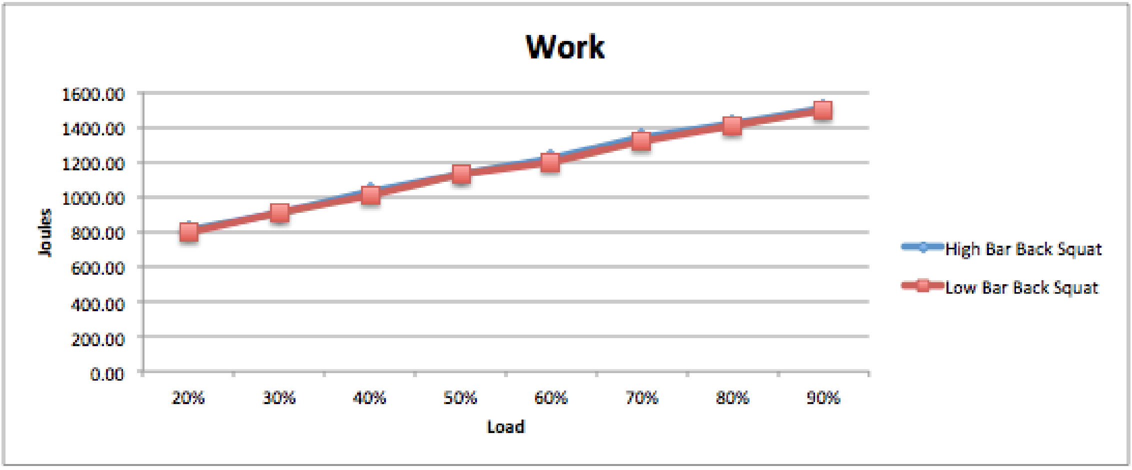
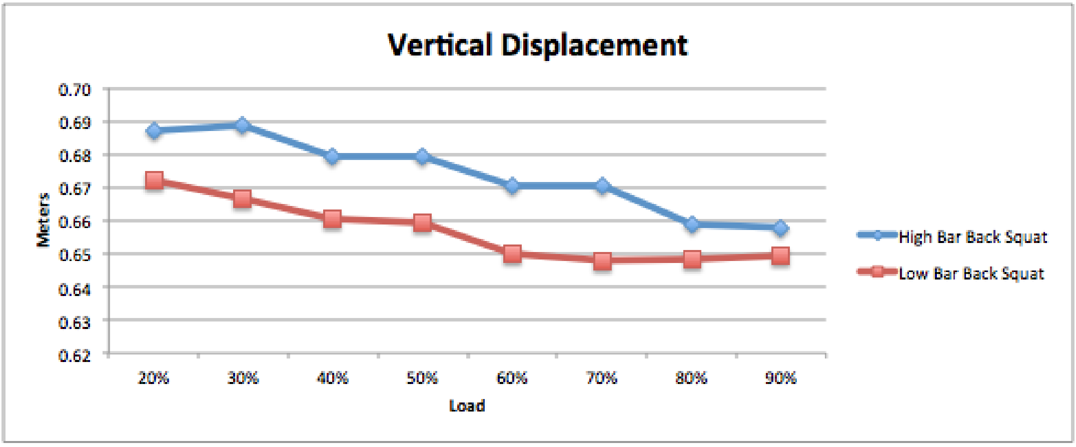


Figure 6 – Changes in Vertical Displacement with Increasing Load



VITA

JACOB GOODIN

Education:	B.S. Kinesiology, Westmont College, Santa Barbara, California 2011 M.A. Kinesiology and Sport Studies, Concentration in Exercise Physiology and Performance, East Tennessee State University, Johnson City, Tennessee 2015
Professional Experience:	Strength Coach, Prevail Conditioning Performance Center, Santa Barbara, California 2011 – 2013 Head Cross Country and Track and Field Coach, Providence Hall High School, Santa Barbara, California 2011 – 2013 Assistant Track and Field Coach, Westmont College, Santa Barbara, California 2012 Instructor, Westmont College, Santa Barbara, California 2012 – 2013 Research Coordinator, Research Institute of Human Movement, Santa Barbara, California 2011 – 2013 Graduate Assistant, East Tennessee State University, Johnson City, Tennessee 2014 – 2015
Publications:	Bazyler, C., Goodin, J., Beckham, G., Santana, H., Swartz, M., Kavanaugh, A., Stone, M., Longitudinal assessment of tennis fitness characteristics in an NCAA Division I tennis player: a case study, 2014