The effect of sex and footwear on dynamic changes during the loaded barbell back squat

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The Effect of Sex and Footwear on Dynamic Changes during the Loaded Barbell Back Squat

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A thesis submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

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FACULTY COMMITTEE:

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Dedication

I would like to dedicate this project to my mother and her mother who continuously supported me in every way throughout my academic career, always held me to the highest expectations, and reminded me of how it important it is that I become an independently thinking, educated, woman of color as a symbol of success to my community. Thank you.
Acknowledgements

There were many people who contributed to the success of this project. I would like to begin by acknowledging my thesis committee first by thanking Dr. Roshna Wunderlich for serving as my thesis advisor and committee chair. Secondly, I would like to thank Dr. Nicholas Luden who has been an influential instructor throughout my graduate studies. Thank you Nick for helping me gain confidence in my intellectual capabilities and my ability to present in front of my peers. I would also like to thank Dr. Christian Carter. Christian you have expanded my understanding of strength and conditioning beyond the textbook and weight room and I feel as though I am a more knowledgeable strength and conditioning specialist and will be a more effective sports performance coach because of you.

Next, I would like to acknowledge the JMU campus community that contributed to my study. I am especially grateful to my JMU Animal Movement Laboratory peers. Your positivity while in the lab, as well as the help you all provided with data collection made the environment more enjoyable which was extremely valuable to me throughout the project.

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Abstract

PURPOSE: The purpose of this study is to examine the effects of sex and footwear on 3D kinematics, power output, and plantar pressure distribution during the loaded barbell back squat. METHODS: Eleven (four male, seven female) recreationally-active individuals completed six sets of three repetitions of the loaded barbell back squat at 60% of their measured 1RM. Using a randomized counterbalanced crossover design, one set was completed in each of the three footwear conditions – weightlifting shoes (WLS), running shoes (RS) and minimalist shoes (MS) – and 3D kinematics, ground reaction force (GRF), and plantar pressure distribution were collected. A two-way 2 (sex) x 3 (footwear) analysis of variances was used to evaluate differences. RESULTS: Females displayed significantly higher ankle plantarflexion and knee abduction at maximum knee flexion compared to males. Males exhibited significantly greater absolute peak power at the ankle, knee, and hip. Males had a lower mean absolute peak power knee to hip ratio in WLS compared to RS and MS while females had similar absolute peak power knee to hip ratios in WLS and RS. Males and females had similar ratios of peak pressure in the hindfoot relative to the total foot in WLS (0.78, 0.79 respectively). There was no interaction between sex and footwear when observing 3D kinematics, absolute peak joint power, and plantar pressure distribution in this study. CONCLUSIONS: Females may need to train in WLS before seeing changes in power distribution that favors hip power output. The influence of footwear could affect males more so than females in their ability to maintain peak pressure in the HF relative to the total foot in order to drive through the heels during the ascent of the loaded barbell back squat.
Chapter One

Introduction

In recent decades, there has been a substantial rise in the number of females participating in sports. The addition of female divisions allow females to compete in sports previously exclusive to male athletes. For example, the International Weightlifting Federation held the first official international competition for female weightlifters in 1987 which was over 100 years after it began hosting the World Weightlifting Championships. Similarly, the International Olympic Committee included a female division in weightlifting at the 2000 Olympic Games in Sydney, Australia nearly 80 years after it became an Olympic sport. Along with these professional additions, female athlete participation is rising accordingly on the pre-professional level. The NCAA reported the net gain in women’s teams from 1988-89 to 2014-2015 was over 3.5 times greater than the net gain in men’s teams (NCAA Sports Sponsorship and Participation Rates Report, p. 9). The growth of females’ participation in sports led researchers to investigate how the biological differences between sexes effect movement biomechanics during athletic activities.

Research has shown notable variations in joint kinematics and muscular activation patterns between sexes during athletic activities. Studies evaluating athletic tasks such as cutting, jumping, and landing show female athletes display greater hip adduction and knee abduction than males (Malinzak et al. 2001, Ford et al. 2005, McClean et al. 2005, Kernozek et al. 2008). Hip adduction with knee abduction is a static measure often denoted as knee valgus. Dynamic measurements observed showing the knee moving into a more valgus position is reported to be caused by poor hip strength (Zeller et al. 2003, Jacobs et al. 2007, Graci et al. 2012, Nakagawa et al. 2012) and induces greater tensile forces on the
anterior cruciate ligament (ACL) (Schoenfeld 2010). While, male athletes often display greater activation of the hamstrings, female athletes often exhibit increased quadriceps activation during athletic activities (Malinzak et al. 2001, Zazulak et al. 2005, Youdas et al. 2007, Ebben et al. 2009). However, failure to activate the hamstrings relative to the quadriceps can be additionally detrimental to the ACL. The hamstrings are responsible for resisting anterior translation of the tibia relative to the femur during dynamic contraction. When the hamstrings cannot resist the force imposed by the quadriceps, the ACL experiences an increased shear force (Schoenfeld 2010). Dynamic knee valgus, poor hip strength, and increased quadriceps activation with decreased hamstring activation are suggested to contribute to the increased incidence of ACL injury in female athletes (Markolf et al. 1995). Thus, in order to prevent injury and enhance sports performance, athletes often participate in strength and conditioning. Strength training often includes many multi-joint weightlifting exercises that mimic the muscle activation patterns experienced during sports. The squat is an exercise frequently used in training programs for athletes to support knee varus and improve strength imbalances (i.e. quadriceps to hamstring activation) by increasing knee stability (Escamilla 2001, Clark et al. 2012).

Squatting engages the musculature surrounding the hip, knee and ankle. Because of how frequently the squat is used, the National Strength and Conditioning Association (NSCA) released a position statement to instruct coaches and athletes in proper squatting technique. In order to maximize the benefits of the squat, the lifter should make an effort to minimize trunk anteroposterior displacement, maintain a near vertical shank, erect torso, and prevent knees valgus (Chandler and Stone 1991). During the squat, center of pressure (COP) is distributed towards the hindfoot when descending and remains so as the lifter
pushes vertically through the heels to return to the initial stance (Dionisio et al. 2008). Pushing through the heels during the ascending phase of the squat is done to maintain stability during the rapid change in center of gravity. In an effort to support proper squat technique and maintain stability, specialized weightlifting shoes (WLS) are usually worn by experienced and professional lifters, male and female alike.

WLS are designed with a heel generally elevated ≥15mm relative to the forefoot, an incompressible sole, and straps that wrap around the midfoot. Although there is limited research exploring footwear while weightlifting, WLS elicit various favorable lifting kinematics such as increased knee flexion (Sato et al. 2013, Sinclair et al. 2014, Hughes and Prescott 2015), increased shank angle (Fortenbaugh et al. 2010, Sato et al. 2012, Hughes and Prescott 2015), and increased ankle range of motion (ROM) (Fortenbaugh et al. 2010, Sato et al. 2012, Sinclair et al. 2014) during the squat when compared to alternate footwear. These kinematic changes shown while wearing WLS coincide with the NSCA guidelines for completing a proper squat. However, while athletes of both sexes utilize WLS, these findings cannot be generalized to females as they repeatedly demonstrate differences in lower limb biomechanics during athletic activities. The subject demographics for all but one study investigating WLS include males only. Results for kinematic and kinetic changes for female athletes utilizing WLS may vary given their differences in muscle activation patterns and joint kinematics.

Although information exclusively observing females in different footwear while weightlifting is not available, results from past studies can be used to design future studies for female and male populations. After which, comparable differences between the sexes can be made and practical significance for the use of different footwear for each sex can
be considered. For example, a recent study by Sinclair et al. (2014) compared the loaded barbell back squat in four different conditions: 1) WLS, 2) barefoot inspired footwear 3) running shoes (RS), and 4) barefoot conditions, and found increased peak and mean activation of the rectus femoris muscle in RS compared to barefoot but no differences among the other conditions (Sinclair et al. 2014). Because female’s exhibit increased relative rectus femoris activity in weightlifting and in sports already, WLS might be beneficial to balance training of the hamstrings along with the quadriceps. The compressible soles of RS are designed for repeated shock absorption and their increased compliance could cause the lifter to sink into their shoes under a heavy load. After which, the lift would require a greater time and distance to return to the initial stance, which would explain an increase in muscle activation. However, a recent review by Clark et al. (2012) cited squatting on an unstable base increases muscle activation, yet hinders power output (Clark et al. 2012). When compared to WLS, RS can be considered less stable, and while Sinclair et al. (2014) accounted for increased muscular activity in RS during the loaded barbell back squat, researchers did not report on power production. Because WLS are designed with an incompressible sole they may elicit a reduced time to complete the lift and subsequently sustain power output.

Moreover, research has yet to elucidate the influence of sex and footwear on kinetic and kinematic variables such as power output at specific joints during the squat and plantar pressure distribution. For example, research shows females elicit greater ankle dorsiflexion (Zeller et al. 2003) and trunk lean (Nakawaga et al. 2012) than males during the squat. Whitting et al. (2015) demonstrated greater ankle dorsiflexion in RS when compared to WLS and no differences in trunk lean (Whitting et al. 2015). Because of the stiff sole and
increased ankle ROM in WLS, females increased dorsiflexion may be eliminated when lifting in WLS. Further, while trunk lean is often used as an observational indicator of balance and stability during squatting it would be beneficial to investigate whether the increased trunk lean females have previously exhibited during the squat was potentially influenced by footwear. Additionally, plantar pressure distribution is variable between sexes during play which has led researchers to propose sex specific footwear in sports such as soccer (Sims et al. 2007, Queen et al. 2010). However, these sex differences in plantar loading patterns have yet to be investigated during weightlifting.

Although there is ample literature investigating the squat, there is less examining the influence of footwear on squatting, and none investigating the influence of footwear on squatting between sexes. The purpose of this study is to examine the effects of footwear and sex on 3D kinematics, power output, and plantar pressure distribution during the loaded barbell back squat. This study will test the hypotheses that there are sex differences in the effect of footwear on kinematics, power, and plantar pressure distribution during the loaded barbell back squat. We predict females will show greater ankle dorsiflexion, knee abduction, and hip adduction than males. We also predict females will show less ankle dorsiflexion, knee abduction, and hip adduction when in WLS when compared to RS and MS. Further, we predict females will show greater knee and ankle power output than males; however both sexes will show greater overall power output in WLS compared to RS and MS. Additionally, we predict peak plantar pressure will be greatest in WLS and least in MS. We also predict peak pressure in the hindfoot relative to the forefoot, as well as the hindfoot relative to the total foot will be greatest in WLS for both sexes.
Chapter Two

Methodology

Participants

Seven to ten recreationally active subjects of each sex will be recruited from the JMU campus community and potential subjects will also be recruited from fitness facilities
in Harrisonburg, VA. Inclusion criteria includes 18 to 35 years of age, non-smokers, and free from any musculoskeletal injury within the previous year. Selected subjects will have a minimum of 2 years lifting experience in the loaded barbell back squat and participate in resistance exercise for a minimum of 60 minutes per day, for at least three days per week. They will also have experience lifting in at least two of the three footwear conditions. Subjects will provide written consent following a verbal and written explanation of testing procedures. The procedure has been approved by the James Madison University Institutional Review Board.

Experimental Design
Subjects will test on two separate occasions separated by no less than 7 days and no more than 10 days. For the first test session each subject will complete a one repetition maximum (1RM) assessment for the high bar back squat in their preferred footwear. The second test session will be an exercise test. During the exercise test session, each subject will complete two trials of the high bar back squat in WLS, RS, and MS for a total of six sets with three repetitions per sets using a 60% of their 1RM. The order of footwear within the exercise test session will be a random, counterbalanced, crossover design. Subjects will be instructed to be hydrated upon arrival. They will be asked to avoid caffeine for 6h and alcohol consumption 24h prior to all testing sessions. This will reduce the likelihood of a medical emergency due to dehydration. Both test sessions will be completed with spotters and under the supervision of an NSCA Certified Strength and Conditioning Specialist. Subjects will be instructed to squat to parallel, for all sessions. A single investigator will visually determine when each subject has reached parallel. For this study, parallel is determined as when the hip marker aligns with the knee marker (see Figure 1-1,2). 3D
kinematics, ground reaction force (GRF), power output, and plantar pressure will be collected in each footwear condition.

![Figure 1-1. Sagittal view of squatting form for all lifts. A, starting and ending position; B, parallel position.](image)

![Figure 1-2. Anterior view of squatting form for all lifts.](image)

**1RM Assessment**
Each subject will complete a 1RM assessment in their preferred footwear in the James Madison University Bridgeforth Stadium weight room. Each subject will perform a standardized warm up consisting of 10 bodyweight squats and dynamic stretching. Subjects will then immediately progress to eight repetitions of their perceived 40% 1RM. After a
three minute rest period, subjects will progress to five repetitions of their perceived 60% 1RM, rest for 3-5 minutes and then complete three repetitions of their perceived 75% 1RM. Following five minutes rest, the subjects will complete one repetition at their perceived 90% 1RM, rest for five minutes, then attempt a maximal lift. There will be up to three subsequent maximal lift attempts with five minutes rest between each effort. Each attempt will increase by 2.5-5.0kg until the subject cannot successfully ascend to the initial stance from a parallel position.

**Exercise Testing**

Each subject will return to complete the second test session in the James Madison University Animal Movement Laboratory. Subjects will be asked to wear form-fitted athletic wear such as spandex shorts and a sleeveless top or sports bra so that all anatomical marker locations can be clearly viewed. Subjects will do a standardized warm up that will consist of dynamic stretches and ten unloaded barbell back squats in the high bar position. The warm up will end with the subject completing eight repetitions at their respective 40% 1RM. The subject will then rest for two minutes prior to the start of the test where data collection will begin. Subjects will be instructed to begin with the body erect and descend at a controlled tempo until reaching at least parallel. In a continuous motion, the subject will ascend explosively with the intention of moving the bar as fast as possible to end at the initial erect stance. The test will consist of two trials. For each trial, the subject will complete three sets of three repetitions of the high bar back squat at a load of 60% 1RM. For the three sets in a single trial, each subject will wear a different type of shoe per set. There will be a four minute rest period after each set and a ten minute rest period between trials.
**Instrumentation**

*3D kinematic analysis*

Hip flexion and adduction, knee flexion and abduction, and ankle dorsiflexion will be measured using a Qualisys 3D motion analysis system (Qualisys AB, Gothenburg Sweden). Retroreflective markers will be placed on the subjects at the posterior calcaneus and first and fifth metatarsal heads (foot), medial and lateral malleoli (ankle), medial and lateral femoral epicondyle (knee), anterior (ASIS) and posterior (PSIS) superior iliac spine, greater trochanter, (hip) greater tubercle of the humerus (shoulder), and a marker will also be placed on the bar itself. 3D kinematic information will be collected using Qualisys optical motion capture system (Qualisys AB, Gothenburg Sweden).

*Kinetic analysis*

GRF will be collected using dual force plates (AMTI Inc., Newton, MA). Peak power output will be calculated from bar velocity and GRF and peak power of the hip (1), knee (2) and ankle (3) will be calculated from inverse dynamics using data collected from the force plate and the 3D motion capture system (see Figure 2).

In order to analyze pressure data, the foot will be divided into four anatomical regions: medial forefoot (MFF), medial hindfoot (MHF), lateral forefoot (LFF), and lateral hindfoot (LHF) (see Figure 3). The foot will be divided in the sagittal plane (frontal axis) from the third metatarsal to the calcaneus to define the medial and lateral foot regions. The forefoot will comprise the area of the foot anterior to the most posterior base of the navicular and cuboid bones and the hindfoot will include the calcaneus and talus. Peak pressure and impulse from each region will be collected. From these data, ratios from the hindfoot relative to the forefoot and hindfoot relative to the total foot will also be calculated. All pressure data will be collected using Pedar insoles (Novel GMBH, Munich, Germany).
Figure 2. A, Angle of the hip (1), knee (2), and ankle (3) at parallel; B, the GRF of the force plate used to calculate the power produced at each joint. Sagittal view.

Figure 3. Anatomical regions of the foot used for pressure data analysis. Medial forefoot (MFF), medial hindfoot (MHF) lateral forefoot (LFF), and lateral hindfoot (LHF).
Footwear
Each participant will provide their own footwear for the study. The limited size availability of pressure insoles will restrict the subjects to US men’s sizes 6-10. The footwear in this investigation will include a WLS, RS, and minimalist shoe (MS). A WLS will be characterized by a heel raised ≥ 15mm above the forefoot, with an incompressible sole, and straps that wrap around the midfoot. RS will be considered to be any athletic footwear designed for the purpose of running, with a compressible sole, heel to toe drop of 10-12mm and weight > 8 ounces. MS will be determined as any athletic shoe with a 0-5mm heel to toe drop and weigh < 8 ounces.

Statistical Analysis
In order to normalize timing of each lift, all kinematic and pressure waveforms will be adjusted to 100% of the movement for each trial. Variables measured for each trial are as follows: (1) maximal power output (2) peak power output at the hip, knee, and ankle (3) peak pressure of the forefoot, hindfoot, and total foot and (4) maximal hip flexion and adduction, knee flexion and abduction, and ankle dorsiflexion. Means and standard deviations of each variable for each sex and in each footwear condition will be evaluated. A two way repeated measures analysis of variance (RMANOVA), with a significance level of $p < 0.05$, will be conducted to investigate the influence of sex and footwear on each variable. A chi squared analysis with a significance level of $p < .05$ will be conducted to examine footwear preference and power production. Post hoc pairwise comparisons will be performed using a Tukey adjustment to reduce the likelihood of type one error. Variables that violate the assumption of sphericity will be corrected using the Greenhouse-Geisser adjustment. All statistical assessments will be calculated using SPSS version 22.0 (SPSS Inc., Chicago, IL, USA).
Chapter Three
Manuscript
The Effect of Sex and Footwear on Dynamic Changes during the Loaded Barbell Back Squat

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ABSTRACT

PURPOSE: The purpose of this study is to examine the effects of sex and footwear on 3D kinematics, power output, and plantar pressure distribution during the loaded barbell back squat. METHODS: Eleven (four male, seven female) recreationally-active individuals completed six sets of three repetitions of the loaded barbell back squat at 60% of their measured 1RM. Using a randomized counterbalanced crossover design, one set was completed in each of the three footwear conditions – weightlifting shoes (WLS), running shoes (RS) and minimalist shoes (MS) – and 3D kinematics, ground reaction force (GRF), and plantar pressure distribution were collected. A two-way 2 (sex) x 3 (footwear) analysis of variances was used to evaluate differences. RESULTS: Females displayed significantly higher ankle plantarflexion and knee abduction at maximum knee flexion compared to males. Males exhibited significantly greater absolute peak power at the ankle, knee, and hip. Males had a lower mean absolute peak power knee to hip ratio in WLS compared to RS and MS while females had similar absolute peak power knee to hip ratios in WLS and RS. Males and females had similar ratios of peak pressure in the hindfoot relative to the total foot in WLS (0.78, 0.79 respectively). There was no interaction between sex and footwear when observing 3D kinematics, absolute peak joint power, and plantar pressure distribution in this study. CONCLUSIONS: Females may need to train in WLS before seeing changes in power distribution that favors hip power output. The influence of footwear could affect males more so than females in their ability to maintain peak pressure in the HF relative to the total foot in order to drive through the heels during the ascent of the loaded barbell back squat.
INTRODUCTION

In recent decades, there has been a substantial rise in the number of females participating in sports. The addition of female sports divisions allows females to compete in sports previously exclusive to male athletes. The 2012 Summer Olympics in London, UK was a major milestone for female athletics as it was the first games to have female athletes represented across all sports. Female sport participation is also rising on the pre-professional level. The NCAA reported the net gain in women’s teams from 1988-89 to 2014-2015 was over 3.5 times greater than the net gain in men’s teams (NCAA Sports Sponsorship and Participation Rates Report, p. 9). The growth of female participation in sports has driven research investigating differences in movement biomechanics between sexes during athletic activities.

There are notable variations in joint kinematics between sexes during athletic activities that primarily involve muscles surrounding the hip and knee joints. Female athletes move into greater knee valgus during activity when compared to male athletes (Chappell et al. 2002, Ford, Myer, and Hewett 2003, Russell et al. 2006, Jacobs et al. 2007). Comparative studies show female athletes display greater knee valgus marked by increased hip adduction and knee abduction compared to males during athletic tasks such as cutting, jumping, and landing (Malinzak et al. 2001, Lephart et al. 2002, Ford et al. 2005, McClean et al. 2005, Kernozek et al. 2008). The difference in joint kinematics between sexes is accompanied by alternative muscle activation patterns. While male athletes often display a decreased activation ratio of the quadriceps relative to the hamstrings, female athletes often demonstrate an increased quadriceps to hamstrings activation ratio during athletic activities (Houston and Wojtys 1996, Malinzak et al. 2001, Zazulak et al. 2005, Youdas et
al. 2007, Ebben et al. 2009). The increased quadriceps to hamstrings activation ratio in female athletes is attributed to increased quadriceps activation and has been referred to as knee dominance. As previously noted female athletes exhibit increased hip adduction and knee abduction. This kinematic pattern is suggested to be potentially caused by poor strength in the musculature surrounding the hips which then compels the female athlete to rely on force production in the musculature surrounding the knee for lower limb extension (Powers 2003).

Both dynamic knee valgus (Ford et al. 2005, Hewett et al. 2005, Nagano et al. 2007, Koga et al. 2010, de Marche Baldon et al. 2011) and increased quadriceps activation (Colby et al. 2000, Hiemstra et al. 2004, Nagano et al. 2007, Myer et al. 2009) are argued to be possible mechanisms of non-contact anterior cruciate ligament (ACL) injury among female athletes. Increased muscle activation in the quadriceps permits an increased moment at the knee. This increased knee moment then preloads the ACL. This can be especially disadvantageous when the knee is slightly flexed, an action female athletes have also previously shown during athletic activities (Malinzak et al. 2001). At knee flexion angles less than 30° the ACL is a primary restraint of anterior translation of the tibia relative to the femur (Li et al. 1999, Kanamori et al. 2000). In addition to the ACL, the hamstrings are also responsible for preventing anterior translation of the tibia, yet they are active at all knee flexion angles (Pandy and Shelbourne 1997, Escamilla 2001). However, if female athletes do not effectively activate the hamstrings to match the force generated by the quadriceps, the ACL will need to insure the knee joint where the athlete lacks in hamstring activation. Yet the ACL alone cannot sufficiently resist the force of the quadriceps while simultaneously preventing anterior translation of the tibia relative to the femur. Thus, to
address quadriceps dominance in order to elude potential ACL injury, strength and conditioning programs for female athletes primarily focus on strengthening hip and knee musculature. This not only increases muscular strength to reduce the likelihood of injury, it also further develops athleticism which in turn enhances sports performance (Cichanowski et al. 2007). Strength training often includes many multi-joint resistance training exercises that mimic the muscle activation patterns experienced during sports. The squat is an exercise frequently used in training programs for athletes to support knee varus and engage all lower extremity musculature (Escamilla 2001, Clark et al. 2012).

Because of the frequency and popularity in using the squat exercise in athletic strength and conditioning programs, the National Strength and Conditioning Association (NSCA) released a position statement to instruct coaches and athletes in proper squatting technique. In order to maximize the benefits of the squat, the lifter should make an effort to (1) minimize trunk anteroposterior displacement by maintaining an erect torso, (2) keep a near vertical shank, and (3) prevent knees valgus (Chandler and Stone 1991). During the squat, center of pressure (COP) should be distributed towards the hindfoot when descending and remain so as the lifter pushes vertically through the heels to return to the initial stance (Dionisio et al. 2008). Pushing through the heels during the ascending phase of the squat is done to maintain stability during the rapid change in the position of the center of gravity. In an effort to support proper squat technique and maintain stability, specialized weightlifting shoes (WLS) are usually worn by experienced and professional lifters, male and female alike. However, WLS are becoming increasingly popular among novice and intermediate lifters with the growing popularity of CrossFit and the sport of weightlifting.
WLS are designed with a heel generally elevated $\geq 15$mm relative to the forefoot, an incompressible sole, and straps that wrap around the midfoot. Although there is limited research exploring footwear while weightlifting, WLS facilitate various favorable lifting kinematics such as increased knee flexion (Sato et al. 2013, Sinclair et al. 2014, Hughes and Prescott 2015, Legg et al. 2016), increased shank angle (Fortenbaugh et al. 2010, Sato et al. 2012, Hughes and Prescott 2015), increased ankle range of motion (ROM) (Fortenbaugh et al. 2010, Sato et al. 2012, Sinclair et al. 2014) and decreased ankle dorsiflexion angle (Whitting et al. 2015, Legg et al. 2016) during the squat when compared to alternate footwear. Increased knee flexion results in a greater squat depth and increased muscle activation, while the increased shank angle, increased ankle ROM, and decreased ankle dorsiflexion angle produce a more upright stance. Completing the squat with excessive anterior translation can result in a transfer of load from the posterior kinetic chain. This can potentially unevenly distribute the load and cause the lifter to elevate their heels off the ground in order to attempt to maintain balance. Lifting the heels from the ground is not a safe or effective practice when squatting because it can cause the lifter to lose balance. The kinematic changes shown while wearing WLS coincide with the NSCA guidelines for completing a proper squat. However, while athletes of both sexes utilize WLS, these findings cannot be generalized to females as they repeatedly demonstrate differences in lower limb biomechanics during athletic activities and these differences are consistent when squatting (Zeller et al. 2003, Graci et al. 2012, and Nakagawa et al. 2012).

Sinclair et al. (2014) compared the loaded barbell back squat in four different conditions: 1) WLS, 2) barefoot inspired footwear 3) running shoes (RS), and 4) barefoot, and found increased peak and mean activation of the rectus femoris muscle in RS compared
to barefoot as well as a decrease in ankle dorsiflexion, but no differences among the other conditions (Sinclair et al. 2014). Because females exhibit increased relative rectus femoris activity in weight lifting exercises and in sports already, we predict WLS could be beneficial to balance training of the hamstrings along with the quadriceps. The compressible soles of RS are designed for repeated shock absorption and their increased compliance could cause the lifter to sink into their shoes under a heavy load, after which, the lift would require a greater time and distance to return to the initial stance, which could explain an increase in muscle activation. A recent review by Clark et al. (2012) cited squatting on an unstable base increases muscle activation, yet hinders power output (Clark et al. 2012). When compared to WLS, RS can be considered less stable, and while Sinclair et al. (2014) accounted for increased muscular activity in RS during the loaded barbell back squat, they did not report on power production. Because WLS are designed with an incompressible sole they may elicit a reduced time to complete the lift and subsequently sustain power output. Research has yet to elucidate the influence of sex and footwear on kinetic and kinematic variables such as power output at specific joints during the squat and plantar pressure distribution. Additionally, plantar pressure distribution is variable between sexes during play. This has led researchers to propose sex specific footwear in sports such as soccer (Sims et al. 2007, Queen et al. 2010). However, these sex differences in plantar loading patterns have yet to be investigated during weightlifting.

Although there is ample literature investigating the squat, there is little known about the effect of sex and footwear on squatting. The purpose of this study is to examine the effects of sex and footwear on 3D kinematics, power output, and plantar pressure distribution during the loaded barbell back squat. We will test the hypotheses that there are
sex differences, footwear differences, and sex differences in the effect of footwear on kinematics, power, and plantar pressure distribution during the loaded barbell back squat. We predict females will show greater ankle dorsiflexion, knee abduction, and hip adduction than males during a loaded barbell back squat. This prediction is supported by the kinematic patterns of females in previous research that shows female’s exhibit increased ankle dorsiflexion, knee abduction and hip adduction compared to males (Malinzak et al. 2001, Lephart et al. 2002, Zeller et al. 2003, Ford et al. 2005, McClean et al. 2005, Kernozek et al. 2008, Graci et al. 2012, and Nakagawa et al. 2012). We also predict females will show less ankle dorsiflexion when in WLS when compared to RS and MS. The increased ankle plantarflexion facilitated by the elevated heel of WLS causes a reduced ankle dorsiflexion angle throughout the lift and thus helps maintain a vertical shank. Since ankle dorsiflexion is decreased while wearing WLS in males, it would be unlikely for it to increase for females given the elevated heels that put the foot in a more plantarflexed position. Additionally, WLS shoes are designed with medially posted midsoles and will likely reduce pronation of the foot. Since excessive pronation is often associated with knee abduction (Hewett et al. 2005) and knee abduction is often accompanied by hip adduction (Zeller et al. 2003, Baldon et al. 2011), we predict these will be reduced in WLS. We predict power output at each joint will be greatest in WLS because their decreased compliance will prevent loss of force production compared to RS that are likely to cause the lifter to sink into their shoes and cause an increase in time to return to an erect initial stance. We predict females will show greater knee power output than males. Because females have previously shown increased relative quadriceps activation and are dominant in using this muscle in various athletic tasks including squatting, it may cause them to have
an increased knee power output relative to their hip power output compared to their male counterparts. Lastly, we predict peak plantar pressure will be greatest in WLS because of the stiff sole.

METHODOLOGY

Participants

Eleven (4 male; 7 female) recreationally-active individuals volunteered to participate in this study. Subject characteristics are reported in Table 1. All subjects were non-smokers, free from any musculoskeletal injury within the previous year and had at
least 1 year of lifting experience in the loaded barbell back squat. All subjects were also accustomed to squatting in at least two of the three footwear conditions. Subjects provided written consent following a verbal and written explanation of testing procedures. This study was approved by the James Madison University Institutional Review Board.

**Experimental Design**

Subjects reported for testing on two separate occasions separated by no less than 4 days and no more than 10 days. During the first testing session each subject completed a one repetition maximum (1RM) assessment for the high bar back squat in their preferred footwear. Their 1RM was then used to calculate the load at which they lifted during the second session. During the second testing session each subject completed six sets of three repetitions of the loaded barbell back squat at 60% 1RM. Using a randomized counterbalanced crossover design, one set was completed in each of the three footwear conditions – WLS, RS, and MS – and 3D kinematics, ground reaction force (GRF), and plantar pressure distribution were collected.

For all testing, subjects were instructed to be hydrated upon arrival and asked to avoid caffeine for 6 hours and alcohol consumption 24 hours prior to testing. All testing was completed under the supervision of an NSCA Certified Strength and Conditioning Specialist. Subjects were required to squat to parallel. For this study, parallel was defined by the position where the hip marker aligned with the knee marker (Figure 1).

**1RM Assessment**

Each subject performed a standardized warm-up consisting of five minutes of cycling followed by dynamic stretching and 10 bodyweight squats. Subjects then immediately progressed to ten squats with a standard Olympic barbell and then eight
repetitions of their perceived 40% 1RM. After a three-minute rest period, subjects progressed to five repetitions of their perceived 60% 1RM, rested for 3-5 minutes and then completed three repetitions of their perceived 75% 1RM. Following five minutes rest, the subjects completed one repetition at their perceived 90% 1RM, rested for five minutes, and then attempted a maximal lift. Each subject was then allowed up to three subsequent maximal lift attempts with five minutes rest between each effort. Each attempt was considered successful until the subject could not ascend to the initial stance from a parallel position.

**Exercise Testing**

Subjects wore form-fitted athletic wear such as spandex shorts and a sleeveless top or sports bra so that all anatomical marker locations could be accurately placed and clearly viewed. Subjects completed a standardized warm up consisting of dynamic stretching, ten unloaded barbell back squats in the high bar position, followed by eight repetitions at their respective 40% 1RM. The subject then rested for two minutes prior to the start of the test. Subjects began with the body erect and descended at a controlled tempo until reaching parallel. In a continuous motion, the subject ascended explosively. Subjects were instructed to move the bar as fast as possible to end at the initial erect stance. This session consisted of two trials. Each trial consisted of three sets of three repetitions of the back squat in the high bar position lifting at their respective 60% 1RM. Subjects took a three-minute rest period after each set and a four-minute rest period between trials.

**Instrumentation**

3D kinematics
A six-camera motion capture system (Qualisys AB, Gothenburg Sweden) was used to track 24 retroreflective markers for motion analysis. Markers were placed on the subjects at the posterior calcaneus and first and fifth metatarsal heads (foot), medial and lateral malleoli (ankle), medial and lateral femoral epicondyle (knee), anterior (ASIS) and posterior (PSIS) superior iliac spine, greater trochanter (hip), tip of the acromion (shoulder), and on each end of the bar (Figure 2). Peak hip flexion was measured at parallel (Figure 1, B) as the angle between the pelvis (trochanter, ASIS, PSIS markers) and thigh segment (hip joint center, medial and lateral femoral epicondyle markers) in the sagittal plane (Figure 3, A-1). Peak hip extension was measured, using the same angle as hip flexion, at the beginning and ending erect stance (Figure 1, A) as well as in between each repetition where the angle was the most extended. Peak knee flexion was measured at parallel (Figure 1, B) as the angle between the thigh (hip joint center, medial and lateral femoral epicondyle markers) and shank segment (medial and lateral femoral epicondyles, medial and lateral malleoli) in the sagittal plane (Figure 3, A-2). Peak knee extension was measured, using the same angle as knee flexion, at the beginning and ending erect stance (Figure 1, A) as well as in between each repetition where the angle was the most extended. Peak ankle dorsiflexion was measured at parallel (Figure 1, B) as the angle between the shank segment (medial and lateral femoral epicondyles, medial and lateral malleoli) and foot segment (first and fifth metatarsal heads and calcaneus) in the sagittal plane (Figure 3, A-3). Peak ankle plantarflexion was measured, using the same angle as ankle dorsiflexion, at the beginning and ending erect stance (Figure 1, A) as well as in between each repetition where the angle was the smallest. Hip adduction was measured as the angle between the pelvis (trochanter, ASIS, PSIS) and thigh segment (medial and lateral femoral epicondyle)
in the frontal plane at peak hip extension and again at each peak hip flexion (Figure 3, B-1). Knee abduction was measured as the angle between the thigh (hip joint center and medial and lateral femoral epicondyles) and shank segment (medial and lateral femoral epicondyles, medial and lateral malleoli) in the frontal plane at peak knee extension and again at peak knee flexion (Figure 3, B-2). Hip flexion, extension, and adduction, knee flexion, extension, and abduction, and ankle plantarflexion and dorsiflexion were measured and analyzed using Visual3D (C-Motion Inc, Germantown, MD).

Kinetics

During the concentric phase of the squat, GRF using dual force plates (AMTI Inc., Newton, MA) and 3D motion using Qualisys motion capture system (Qualisys AB, Gothenburg Sweden), both collected at 240Hz, were used to calculate peak power output of the hip, knee, and ankle. For each joint, the moment arm was determined to be the perpendicular distance between the joint axis of rotation and the GRF vector. The moment arm was then multiplied by the force and joint angular velocity to calculate absolute joint power (Figure 4).

Plantar pressure was collected using Pedar insoles (Novel GMBH, Munich, Germany). The foot was divided into nine anatomical regions. Two pre-defined percentage masks were used to analyze these regions. The forefoot (FF), midfoot (MF), and hindfoot (HF) were regions of the foot used to analyze antero-posterior loading (Figure 5A). The medial forefoot (MFF), lateral forefoot (LFF), medial midfoot (MMF), lateral midfoot (LMF), medial hindfoot (MHF), and lateral hindfoot (LHF) were regions of the foot used to analyze medio-lateral loading (Figure 5B). Peak pressure, pressure-time integral, and
force time integral were measured from each region. Peak pressure of the HF relative to the total foot was also calculated as a ratio.

**Footwear**

Subjects provided their own footwear for the study. The footwear in this investigation included a WLS, RS, and minimalist shoe (MS). Each shoe’s characterization was confirmed by a description provided by the manufacturer. A WLS was characterized by a heel raised ≥ 15mm above the forefoot, with an incompressible sole and straps that wrap around the midfoot. RS were considered to be any athletic footwear designed for the purpose of running, with a compressible sole, heel to toe drop of 10-12mm and weigh > 8 ounces. MS were determined as any athletic shoe with a 0-5mm heel to toe drop and weigh < 8 ounces.

**Statistical Analysis**

In order to normalize timing of each lift, all kinematic and pressure waveforms were adjusted to 100% of the movement for each trial. For each trial we measured: 1. Peak power output at the hip, knee, and ankle, 2. Peak pressure, pressure-time integral and force-time integral, of the all defined regions of the foot along with the total foot and 3. Peak hip extension, peak hip flexion and hip adduction at peak hip flexion; peak knee extension, knee flexion and knee abduction at peak flexion; peak ankle plantarflexion and peak ankle dorsiflexion. Means and standard deviations of each variable for each sex and in each footwear condition were aggregated by trial and evaluated. A two-way analysis of variance, with sex as the between factor and footwear as the within factor, was conducted with a significance level of p < 0.05 to investigate the influence of sex, footwear, and interaction between sex and footwear on each variable. All data were tested for equal variances using
Levene’s test and normality using the Shapiro-Wilk test. Data lacking equal variance or normality were analyzed after a log10 transformation was performed. Post hoc pairwise comparisons were performed to determine differences among groups. A Bonferroni adjustment was used to reduce the likelihood of type one error. All statistical assessments were calculated using SPSS version 22.0 (SPSS Inc., Chicago, IL, USA).
RESULTS

3D Kinematic Analysis

Angular kinematic data are displayed in Table 2. Females displayed significantly higher ankle plantarflexion (males: 89.36°, females: 94.30°; mean difference – 4.93°; CI – 2.46, 9.620; F1, 11=4.66, p=0.04) and knee abduction at peak knee flexion (males: -2.33°, females: 2.34°; mean difference – 4.67°; CI – 2.19, 7.16; F1, 11=14.88, p=0.001) than males. Males displayed significantly less peak hip extension (males: 6.93°, females: 19.37°; mean difference – 12.43°; CI – 5.99, 18.87; F1, 11=15.71, p=0.00) and hip adduction at maximum hip extension (males: 9.83°, females: 7.25°; mean difference – 2.58°; CI – 0.42, 4.74; F1, 11=6.022, p=0.02). There were no significant main effects for footwear and no significant interaction between sex and footwear.

Kinetic Analysis

Power

Males exhibited significantly greater absolute peak power at the ankle (57.23 ± 4.28W, 34.14 ± 3.26W; F1, 11 =12.519, p=0.001), knee (224.29 ± 21.93W, 113.90 ± 4.77W; F1, 11=17.66, p < 0.00), and hip (386.76 ± 25.86W, 208.31 ± 6.07W; F1, 11=88.715, p=0.00) (Figure 6). There was no main effect of footwear on power output at each joint. There was no significant interaction between sex and footwear. Although no statistical analysis was performed, a ratio for peak power of the knee relative to the hip was calculated for each footwear condition. Males displayed the lowest knee to hip ratio for absolute peak power in WLS (0.52) and the highest in RS (0.63) with MS resembling a knee to hip ratio closer to that of RS (0.60). Females had similar knee to hip ratios for WLS and RS (0.57 for both) and the lowest knee to hip ratio for MS (0.50). (Table 3, Figure 7.
Peak Pressure

Peak pressure data are displayed in Table 4. An example of plantar pressure distribution in a male subject throughout the squat for MS (top), RS (middle), and WLS (bottom) is displayed in Figure 9. Plantar pressure moved posteriorly during the descent phase of the squat, traveling from the top of the MF and down towards the HF. It then redistributes from the HF back towards the FF during the ascending phase of the squat. There was more pressure in the LFF and somewhat absent pressure in the MMF while in WLS. Males displayed significantly higher peak pressure of the MF (males: 121.16 ± 12.37kPa, females: 101.25 ± 39.51 kPa; F1, 11=5.00, p= 0.034) and MMF (males: 105.66 ± 15.83kPa, females: 72.47 ± 25.45 kPa; F1, 11=14.78, p=0.01) across footwear conditions. There was a significant main effect of footwear on peak pressure of the LFF (F1, 11=4.60, p=0.019) only. Post-hoc pairwise comparisons showed when compared to RS, WLS elicited an increase peak pressure of the LFF (p=0.006) (mean difference 16%, CI – 4-29%). There was no significant interaction between sex and footwear. Although no statistical analysis was performed, a ratio for peak pressure of the HF relative to the total foot was calculated for each footwear condition. Males and females displayed similar ratios for peak pressure of the hindfoot relative to the total foot in WLS (0.79 and 0.78 respectively). While this ratio was reduced in males in RS (0.65) and MS (0.66), it decreased for females in RS (0.70) and increased for females in MS (0.86) (Table 5, Figure 8).

Pressure-time integral
Pressure-time integral data are displayed in Table 6. Females showed significantly higher pressure-time integral of the total foot (males: 601.31 ± 342.16kPa*s, females: 890.16 ± 448.20kPa*s; F1, 11=4.29, p =0.048), HF (males: 387.79 ± 274.68kPa*s, females: 625.26 ± 385.08kPa*s; F1, 11=5.57, p=0.026), and LHF (males: 338.08 ± 233.71kPa*s, females: 568.65 ± 379.53 kPa*s; F1, 11=5.80, p=0.023) across footwear. Females also exhibited higher contact times across footwear (males: 3583 ± 2419ms, females: 5198 ± 1944ms; F1, 11=7.26, p=0.012). There was no main effect of footwear or significant interaction between sex and footwear.

*Force-time integral*

Force-time integral data are displayed in Table 7. There were no significant main effects of sex on force –time integral. There was no significant main effects of footwear. There was no significant interaction between sex and footwear.
DISCUSSION

The purpose of this study was to determine whether males and females exhibited different joint kinematics, joint power, and plantar pressure distribution when back squatting at 60% 1RM in WLS, RS, and MS. Our current findings show sex and footwear influenced joint kinematics, joint power, and plantar pressure distribution, yet there was no significant interaction between sex and footwear in any of the tested parameters. As expected, there was a significant effect of sex on joint kinematics. Specifically, females experienced higher ankle dorsiflexion and increased knee abduction at peak knee flexion compared to males. Contrary to our hypothesis, this increased knee abduction angle in females was not reduced in WLS and was not significantly different among footwear conditions. There could possibly be an angular threshold for which WLS are effective in altering knee abduction. Future investigations may consider comparing changes in knee abduction angle between experienced and inexperienced lifters to conclude whether inexperienced lifters with substantial knee abduction may experience more noticeable benefits with WLS than those who are experienced.

Our next prediction was that females would exhibit higher ankle dorsiflexion than males and their ankle dorsiflexion would be decreased in WLS compared to other footwear conditions. This prediction was based on previous research that showed female athletes exhibited greater ankle dorsiflexion than males and evidence of decreased ankle dorsiflexion in WLS by males. This prediction was not supported. While females exhibited increased ankle dorsiflexion compared to males similar to previous research (Zeller et al. 2003) there were no significant differences among footwear. Our findings differ from previous research investigating sex differences among footwear. Legg et al. (2016) found
WLS elicited decreased ankle dorsiflexion in females who had similar experience to the females in the current study. However, their participants lifted at a self-reported load of 75% 1RM while the participants of our investigation lifted at a load of 60% of their tested 1RM. It is possible we did not see a significant effect in footwear because of the reduced load. Whitting et al. (2015) found a significant reduction in ankle dorsiflexion angle in WLS compared to RS during the loaded barbell back squat and peak ankle dorsiflexion increased at loads of 50-90% 1RM and 70-90% 1RM. However, peak ankle dorsiflexion was not significantly different at 50-70% 1RM. Therefore, the 60% 1RM load utilized in this investigation may have not been a sufficient load to elicit a significant effect in ankle dorsiflexion angle. We also predicted hip adduction at peak hip flexion would be higher for females, yet there were no differences between sexes in hip adduction at peak hip flexion. However, our results showed males had a more hip adduction angle at peak hip extension supplemented by decreased peak hip extension (i.e. males completed each set in a more flexed position at the hip). This contrasts with previous research that observes more hip adduction in females (Malinzak et al. 2001, Lephart et al. 2002, Ford et al. 2005, Hewett et al. 2005, McClean et al. 2005, Kernozek et al. 2008). Upon further review, we observed while all subjects began and ended each set in a fully erect stance, peak hip extension was averaged for each rep at the initial stance, ending stance, and between each repetition. It is likely males subjects did not return to a fully erect stance after each repetition; thus, overall mean peak hip extension was reduced by hip extension angles recorded between each repetition. This is further supported by the overall reduced contact time for male subjects. Therefore, our results do not directly contrast with previous research that shows female athletes exhibit increased initial hip adduction compared to males (Malinzak et al. 2001,
Our findings show similar peak power output at each joint across footwear. Both sexes produced the greatest absolute peak power from the hips and least from the ankles. Our findings of males exhibiting greater power at each joint compared to females is expected because males are heavier, working against a greater absolute weight and thus producing greater force. The ratio of absolute peak knee to hip joint power shows the average knee to hip ratio for males was highest in RS and lowest in WLS (0.63, and 0.52 respectively) (Table 3, Figure 7). Although we did not substantiate statistical significance, practically this can prove to be a noticeable difference in athletic performance. Increased hip power is associated with increased overall peak power (Vanrenterghem et al. 2008) which translates into being a more explosive athlete. In contrast, females displayed similar ratios of knee to hip absolute peak power output between RS and WLS (0.57 for both footwear conditions). This corresponds to the idea of females being more knee dominant compared to males. In order for female athletes to be able to redistribute power to the hip from the knee and reduce knee dominance, they may need to train in WLS which may further permit gains in strength adaptations. Further research should assess if training in WLS could affect mean power output at each joint and if it can increase maximum strength and overall peak power output over time.

Females showed a higher pressure-time integral compared to males and this can be attributed to their increased contact time as peak pressure of the total foot did not differ between sexes. Although peak pressure of the LFF was the only statistically significant difference in peak pressure across footwear (higher in WLS, 132.24kPa, compared to RS,
99.8kPa), obvious differences in the peak pressure of the HF relative to the total foot were observed across footwear (Table 5, Figure 8). As a ratio, the HF to total foot (HF: TF) peak pressure was highest in WLS (0.79) compared to RS (0.65) and MS (0.66) for males. The time process of peak pressure in each shoe for a male subject displays this variation in Figure 9. WLS appear to allow male lifters to distribute an increased peak pressure in the HF in order to drive through the heels. Our findings are evidence WLS are effective in upholding the NSCA recommendations of pushing up through the heel to execute a proper and effective squat movement. In contrast, while the HF: TF peak pressure distribution is similar in WLS between males and females (0.79 and 0.78 respectively), females showed the highest HF: TF peak pressure ratio in MS. This may suggest females are less effected by footwear in their ability to drive through the heels compared to males. This is supported as females have a reduced range amongst footwear in HF: TF ratio compared to males (.08, .14 respectively) and sustain a mean HF: TF peak pressure ratio across footwear (0.78) while males see a reduction in HF: TF peak pressure ratio across footwear (0.70).

Because this study presented several limitations these findings should be interpreted with caution. While eleven subjects can arguably be a sufficient sample size to recognize significant effects, the unequal sizes of each group stood to be a substantial limiting factor. Fewer male subjects were recruited due to limited resources. Specifically, pressure insole availability limited our subject selection to males and females fitting a US men’s sizes 6-10. The unequal sample size was a major factor in our observation of unequal distribution and variances in some selected variables. Because this violates a necessary assumption to conduct a reliable two-way ANOVA, we transformed pressure data using a logarithm. However, this was not feasible for joint angle data due to negative values. Further, a
nonparametric test for statistical analysis such a Friedman would require a blocking variable which this procedure does not possess. Therefore, future research should make sample size a main priority in order to address unequal distribution and variance. Another limiting factor of this study was the variability of the footwear. While there were general specified criterion met for each shoe type, each subject provided their own shoes and variability could exist due to wear of the shoes and/or possibly experience lifting in the shoes. For example, the compliance of the running shoes for one subject could be higher or lower compared to the compliance of the running shoes for another subject depending on the frequency of use and/or novelty of the shoe altogether. Providing the footwear would eliminate this variability and increase the reliability of findings. Additionally, we only required weightlifting experience in two of the three shoes tested. This is important because for some subjects, familiarity may have influenced squat performance so much so as to consider comfort as a covariate in this procedure. Finally, while there were only two investigators responsible for anatomical marker placement, the reliability within collection measurements was not tested. Although there may be further limiting factors of this study, these posed the greatest concern for the researchers and should be taken into account when interpreting the results.

**CONCLUSIONS**

3D kinematics, joint power, and plantar pressure distribution are influenced in the high bar back squat when lifting explosively at 60% 1RM and wearing different types of footwear. There was no interaction between sex and footwear when observing joint
kinematics, absolute peak joint power, and plantar pressure distribution in this study. While we observed absolute peak joint power output was similar across footwear, the ratio of knee to hip peak power varied among footwear with WLS eliciting the lowest absolute peak knee to hip power output in males, females displayed similar peak knee to hip power output in WLS and RS. Future research should assess if training in WLS could influence strength gains and overall peak power output. If WLS produce a contrast between the sexes, it may have implications to using WLS for adaptation specific purposes. Lastly, the HF:TF peak pressure varied among footwear. Males showed a greater range in their ratio of H:TF peak pressure than females which may implicate males are more influenced by footwear in their ability to maintain a relatively high peak pressure in the HF to drive through the heels during the squat.

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41. Youdas JW, Hollman JH, Hitchcock JR, Hoyme GJ, Johnsen JJ. Comparison of hamstring and quadriceps femoris electromyographic activity between men and


Table 1. Subject Demographics

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Descriptive data for all subjects. Mean (SD).
Table 2. Angular kinematic parameters (°).

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<td>(6.37)</td>
<td>(6.32)</td>
<td>(8.27)</td>
<td>(8.80)</td>
<td>(9.92)</td>
<td>(9.35)</td>
</tr>
<tr>
<td>Hip Adduction at</td>
<td>10.06</td>
<td>10.00</td>
<td>9.43</td>
<td>7.12</td>
<td>7.30</td>
<td>7.32</td>
</tr>
<tr>
<td>Extension*</td>
<td>(3.49)</td>
<td>(3.40)</td>
<td>(3.62)</td>
<td>(2.76)</td>
<td>(2.30)</td>
<td>(2.57)</td>
</tr>
<tr>
<td>Hip Flexion</td>
<td>84.92</td>
<td>88.66</td>
<td>86.82</td>
<td>85.64</td>
<td>86.23</td>
<td>82.05</td>
</tr>
<tr>
<td></td>
<td>(21.52)</td>
<td>(23.00)</td>
<td>(19.63)</td>
<td>(17.61)</td>
<td>(16.27)</td>
<td>(14.98)</td>
</tr>
<tr>
<td>Hip Adduction at</td>
<td>20.37</td>
<td>21.05</td>
<td>22.02</td>
<td>24.01</td>
<td>23.75</td>
<td>21.74</td>
</tr>
<tr>
<td>Flexion</td>
<td>(9.79)</td>
<td>(10.72)</td>
<td>(6.85)</td>
<td>(6.82)</td>
<td>(4.81)</td>
<td>(5.41)</td>
</tr>
</tbody>
</table>

Values for weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) reported as Mean (SD). Females showed significantly increased ankle plantarflexion and knee abduction at peak flexion. Males showed significantly increased hip extension and adduction at peak extension due to failure to return to initial erect stance. (*) Significant effect for sex.
Table 3. Knee to hip ratio of absolute peak power.

<table>
<thead>
<tr>
<th></th>
<th>WLS</th>
<th>RS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>0.52</td>
<td>0.63</td>
<td>0.6</td>
</tr>
<tr>
<td>Females</td>
<td>0.57</td>
<td>0.57</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Values for weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) reported as a ratio of absolute peak power of the knee relative to absolute peak power of the hip.
Table 4. Peak Pressure (kPa) data.

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS</td>
<td>RS</td>
</tr>
<tr>
<td><strong>Total Foot</strong></td>
<td>244.25 (54.7)</td>
<td>243.32 (34.7)</td>
</tr>
<tr>
<td><strong>FF</strong></td>
<td>220 (61)</td>
<td>221.03 (21.8)</td>
</tr>
<tr>
<td><strong>MFF</strong></td>
<td>215.39 (67.2)</td>
<td>220.12 (22.3)</td>
</tr>
<tr>
<td><strong>LFF†</strong></td>
<td>111.55 (15.2)</td>
<td>108.62 (23.3)</td>
</tr>
<tr>
<td><em><em>MF</em>†</em>*</td>
<td>119.85 (12.4)</td>
<td>119.76 (10.5)</td>
</tr>
<tr>
<td><em><em>MMF</em>†</em>*</td>
<td>102.18 (21)</td>
<td>104.20 (12)</td>
</tr>
<tr>
<td><strong>LMF</strong></td>
<td>113.96 (16.9)</td>
<td>109.52 (16.3)</td>
</tr>
<tr>
<td><strong>HF</strong></td>
<td>160.51 (20.8)</td>
<td>157.23 (25.9)</td>
</tr>
<tr>
<td><strong>MHF</strong></td>
<td>154.21 (26.6)</td>
<td>154.61 (53.7)</td>
</tr>
<tr>
<td><strong>LHF</strong></td>
<td>154.23 (17.6)</td>
<td>145.48 (51.2)</td>
</tr>
</tbody>
</table>

Values for weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) reported as Mean (SD). Males displayed significantly higher peak pressure of the MF (p= 0.034) and MMF (p=0.01). There was a significant main effect of footwear on peak pressure of the LFF only. Post-hoc pairwise comparisons showed when compared to RS, WLS elicited an increase peak pressure of the LFF (p=0.006) (mean difference 16%, CI – 4-29%). (*) Significant effect for sex (†) Significant effect for footwear, RS v WLS.
Table 5. Hindfoot to total foot ratio of peak pressure.

<table>
<thead>
<tr>
<th></th>
<th>WLS</th>
<th>RS</th>
<th>MS</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>0.79</td>
<td>0.65</td>
<td>0.66</td>
<td>0.7</td>
</tr>
<tr>
<td>Females</td>
<td>0.78</td>
<td>0.7</td>
<td>0.86</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Values for weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) reported as a ratio of peak pressure of the HF relative to the total foot.
Table 6. Pressure-time integral (kPa*s) data.

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS</td>
<td>RS</td>
</tr>
<tr>
<td>Total Foot*</td>
<td>534 (349)</td>
<td>487 (163)</td>
</tr>
<tr>
<td>FF</td>
<td>430 (264)</td>
<td>448 (170)</td>
</tr>
<tr>
<td>MFF</td>
<td>414 (276)</td>
<td>440 (180)</td>
</tr>
<tr>
<td>LFF</td>
<td>238 (149)</td>
<td>237 (77)</td>
</tr>
<tr>
<td>MF</td>
<td>348 (311)</td>
<td>253 (94)</td>
</tr>
<tr>
<td>MMF</td>
<td>321 (324)</td>
<td>219 (109)</td>
</tr>
<tr>
<td>LMF</td>
<td>318 (270)</td>
<td>222 (67)</td>
</tr>
<tr>
<td>HF*</td>
<td>353 (275)</td>
<td>269 (77)</td>
</tr>
<tr>
<td>MHF</td>
<td>342 (278)</td>
<td>265 (80)</td>
</tr>
<tr>
<td>LHF*</td>
<td>323 (244)</td>
<td>229 (57)</td>
</tr>
</tbody>
</table>

Values for weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) reported as Mean (SD). Females showed significantly higher pressure-time integral of the total foot (\(p=0.048\)), HF (\(p=0.026\)), and LHF (\(p=0.023\)) across footwear. Females also exhibited higher contact times across footwear (\(p=0.012\)). There was no main effect of footwear or significant interaction between sex and footwear.
Table 7. Force-time integral (%BW*s) data.

<table>
<thead>
<tr>
<th></th>
<th>Males</th>
<th></th>
<th></th>
<th>Females</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS</td>
<td>RS</td>
<td>WLS</td>
<td>MS</td>
<td>RS</td>
<td>WLS</td>
</tr>
<tr>
<td>Total Foot</td>
<td>376 (337)</td>
<td>297 (91)</td>
<td>421 (275)</td>
<td>441 (201)</td>
<td>359 (243)</td>
<td>451 (246)</td>
</tr>
<tr>
<td>FF</td>
<td>133 (95)</td>
<td>136 (43)</td>
<td>210 (125)</td>
<td>193 (109)</td>
<td>149 (111)</td>
<td>217 (118)</td>
</tr>
<tr>
<td>MFF</td>
<td>81 (62)</td>
<td>82 (29)</td>
<td>123 (81)</td>
<td>113 (64)</td>
<td>93 (76)</td>
<td>134 (80)</td>
</tr>
<tr>
<td>LFF</td>
<td>52 (33)</td>
<td>54 (20)</td>
<td>87 (46)</td>
<td>80 (51)</td>
<td>55 (37)</td>
<td>82 (44)</td>
</tr>
<tr>
<td>MF</td>
<td>133 (157)</td>
<td>81 (43)</td>
<td>64 (51)</td>
<td>68 (37)</td>
<td>91 (61)</td>
<td>44 (34)</td>
</tr>
<tr>
<td>MMF</td>
<td>66 (88)</td>
<td>35 (27)</td>
<td>20 (23)</td>
<td>19 (13)</td>
<td>30 (25)</td>
<td>7 (4)</td>
</tr>
<tr>
<td>LMF</td>
<td>67 (69)</td>
<td>45 (17)</td>
<td>44 (28)</td>
<td>49 (29)</td>
<td>61 (44)</td>
<td>37 (33)</td>
</tr>
<tr>
<td>HF</td>
<td>108 (89)</td>
<td>79 (27)</td>
<td>146 (103)</td>
<td>178 (88)</td>
<td>118 (85)</td>
<td>189 (131)</td>
</tr>
<tr>
<td>MHF</td>
<td>61 (48)</td>
<td>47 (15)</td>
<td>89 (68)</td>
<td>108 (46)</td>
<td>66 (43)</td>
<td>101 (58)</td>
</tr>
<tr>
<td>LHF</td>
<td>47 (41)</td>
<td>31 (11)</td>
<td>57 (34)</td>
<td>69 (52)</td>
<td>51 (43)</td>
<td>88 (75)</td>
</tr>
</tbody>
</table>

Values for weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) reported as Mean (SD). There were no significant differences for sex or footwear or significant interaction between sex and footwear.
Figure 1. Squat form

A. 

B.
Figure 2. Marker placement and pressure data receiver. Left, anterior view; middle, lateral view; right, posterior view.
Figure 3. Joint angles used for kinematic analysis.
Figure 4. Joint moments and GRF used for joint power calculation
Figure 5. Anatomical regions of the foot illustrated on the left foot.
Figure 6. Absolute Peak Power (W)
Figure 7. Knee to hip ratio for absolute peak power
Figure 8. Hindfoot to total foot ratio for peak pressure
Figure 9. Time process of plantar pressure for a male subject for a single repetition in MS (top), RS (middle), and WLS (bottom).
FIGURE LEGENDS

Figure 1.
Squat form for all testing.

A – Starting and ending stance; subjects were instructed to begin and end with knees and hips fully extended.

B – Parallel; subjects descended in a controlled manner until the lateral femoral epicondyle marker aligned with the trochanter marker. Subjects were then instructed to ascend back to the initial stance with the intention of moving the bar as quickly as possible.

Figure 2.
Markers were placed on the subjects at the posterior calcaneus and first and fifth metatarsal heads (foot), medial and lateral malleoli (ankle), medial and lateral femoral epicondyle (knee), anterior (ASIS) and posterior (PSIS) superior iliac spine, greater trochanter (hip), tip of the acromion (shoulder), and on each end of the bar. The pressure insoles were attached to a bluetooth receiver maintained in a waist belt that transmitted plantar pressure values to a program on a laptop. Left, anterior view; middle, lateral view; right, posterior view.

Figure 3.

A –
(1) Peak hip flexion was measured at parallel (Figure 1, B) and peak hip extension was measured, using the same angle as peak hip flexion, at the beginning and ending erect stance (Figure 1, A) as well as in between each repetition where the angle was the most extended.

(2) Peak knee flexion was measured at parallel (Figure 1, B) and peak knee extension was measured, using the same angle as knee flexion, at the beginning and ending erect stance (Figure 1, A) as well as in between each repetition where the angle was the most extended.

(3) Peak ankle dorsiflexion was measured at parallel (Figure 1, B) and peak ankle plantarflexion was measured, using the same angle as ankle dorsiflexion, at the beginning and ending erect stance (Figure 1, A) as well as in between each repetition where the angle was the smallest.

B –
(1) Hip adduction was measured at peak hip extension and again at each peak hip flexion.

(2) Knee abduction was measured at peak knee extension and again at each peak knee flexion.

Figure 4.
Dotted line represents GRF vector. Perpendicular distance from hip joint (1), knee joint (2), and ankle joint (3) to GRF vector and adjacent angle represents the moment arm and joint angle used to calculate power at each joint.
**Figure 5.**

A – Forefoot (FF), midfoot (MF), and hindfoot (HF) used to analyze anteroposterior pressure distribution represented on a left foot.

B – Medial forefoot (MFF), lateral forefoot (LFF), medial midfoot (MMF), lateral midfoot (LMF), medial hindfoot (MHF), and lateral hindfoot (LHF) used analyze mediolateral pressure distribution represented on a left foot.

**Figure 6.**

Absolute peak power of the hip, knee, and ankle, in weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) in males and females. Males showed greater absolute peak power at each joint due being heavier than females (78.9 ± 1.5kg, 61.9 ± 3.5kg, respectively) and lifting at a greater 60% 1RM (87.1 ± 8.1kg, males, 49.2 ± 8.8kg, females).

**Figure 7.**

Knee to hip ratio for absolute peak power in weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) in males and females. Males show a lesser ratio in WLS (0.52) and the highest in RS (0.63) with MS more closely resembling RS (0.60). Females show similar ratios for WLS and RS (0.57 for both) with a lesser ration in MS (0.50).

**Figure 8.**

Hindfoot to total foot ratio for peak pressure in weightlifting shoes (WLS), running shoes (RS), and minimalist shoes (MS) in males and females. Similar ratios between males and females in WLS (0.79, 0.78 respectively). Females had their highest ratio in MS (0.86) while males highest was in WLS (0.79). Compared to WLS, males experienced and a reduced mean ratio across footwear (0.70) while we observed an unchanged mean ratio across footwear in females (0.78).

**Figure 9.**

The time process of peak pressure in MS (top), RS (middle), and WLS (bottom) for a male subject during a single repetition in each respective set of his first trial. These time processes display the variation in peak pressure of the HF relative to the total foot.
Consent to Participate in Research

Identification of Investigators & Purpose of Study

You are being asked to participate in a research study conducted by Ameera Teal, Roshna Wunderlich Ph.D., and Christian Carter Ph.D. from James Madison University. The purpose of this study is to examine the effects of footwear and sex on 3D kinematics, power output, and plantar pressure distribution during the loaded barbell back squat. Additionally, this study aims to determine whether weightlifting shoes enhance power production and squat technique. This study will contribute to the completion of Ameera’s master’s thesis.

Time Required

Participation in this study will require approximately 2 hours of your time. There will be two testing sessions separated by one week; the first session should take about 30-45min and the second session no more than 75min of your time.

Research Procedures

Should you decide to participate in this study, you will be asked to sign this consent form once all your questions have been answered to your satisfaction.

Prior to participating in this study you will be asked questions about your experience in weightlifting, lifestyle behaviors, and physical characteristics (i.e. training years, shoe size, smoking status, activity level, height, weight etc.). This information will help us determine if you meet the inclusion criteria for this study. This study requires that you own and bring weightlifting shoes, running shoes, and minimalist shoes to be tested in. We also ask that you attend each session wearing form-fitted athletic wear (i.e. spandex shorts, sports bra for female participants etc.). This will allow us to identify anatomical landmarks on which to place reflective markers. It will also allow the cameras to view the markers. This study consists of two testing sessions separated by one week. Each session should take approximately one hour of your time. Testing sessions will be sex exclusive. The first testing session will take place in the Bridgeforth Stadium weightroom and the second session in the JMU Animal Movement Laboratory located on the second floor of the Bioscience building in room 2012.

Visit one: One Repetition Max Assessment (1RM)

During the first testing session you will be tested for 1RM in the loaded barbell back squat. Upon arrival we will assign you a number as an identifier and measure your height and weight while you are barefoot. For this assessment you are permitted to wear the shoe of your preference. You will warm up with 10 bodyweight squats and then immediately perform eight repetitions of the back squat in the high bar position using a load that is 40% of what you believe you can maximally lift for this exercise. After a three minute rest period, you will then complete five repetitions at your perceived 60% 1RM, rest for 3-5 minutes and then complete three repetitions of your perceived 75% 1RM. Following five minutes rest, you will then complete one repetition at your perceived 90% 1RM, rest for
five minutes, then attempt a maximal lift. You will be given up to three subsequent maximal lift attempts with five minutes rest between each effort. Each attempt will increase by 2.5-5.0kg if necessary until you cannot successfully ascend to the initial stance from a parallel position. However, you will have the opportunity to refuse lifting after any maximal attempt if you feel you have achieved a maximal effort. During this session you should descend to parallel at a controlled tempo and ascend at a moderate tempo as well. For this study, parallel is considered to be when the hip crease aligns with the knee joint. A certified strength and conditioning specialist will be available to spot during each repetition. There will also be an investigator to notify you when you reach parallel. If you do not descend to parallel for any of the repetitions you will be asked to repeat the repetition until you can adequately complete the lift.

Visit two: Exercise Assessment
During the second testing session we will measure your height and weight while you are barefoot. You will be given a randomized order of which footwear you will complete each set. You will then be fitted for pressure insoles that will be placed in your shoes prior to each set. Markers will be placed on the bar and your foot, ankle, knee, hip, and shoulder for the camera to track movement. Surface electromyographic electrodes will be attached to your thigh muscles. In order to enhance the conductivity of these electrodes we will clean the area for electrode attachment with alcohol and lightly rub it with fine sand paper.

You will be asked to complete a total of 18 repetitions of the high bar back squat (after a warmup with 10 repetitions of the bar alone and five repetitions at 40% max) while being videotaped. The bar will be loaded at 60% of your 1RM obtained from the previous visit. The 18 repetitions will be divided into six sets of three repetitions, each in different footwear. Each set will be separated by at least five minutes. When you un-rack the weight, you will be asked to take up to 2 steps backwards and stand on force plates that will be used to collect data on force and power production. It is absolutely necessary that you descend to parallel at a controlled tempo for each repetition. During this testing session, we ask that after your reach parallel, you ascend explosively to return to the initial stance. When you ascend explosively we are asking you to aim for maximal power output.

Risks
The investigators perceives the possible risks of participation in this study are no more than the risks you would experience weightlifting on your own. The risks of weightlifting include acute fatigue, and muscle soreness 24-48 hours after completion. Participation in this study requires you to be “low risk” in reference to the American College of Sports Medicine’s Guidelines for Exercise Testing and Prescription. Exercise testing of low risk individuals does not permit physician supervision. In the event there is a medical emergency, the researchers have developed an emergency plan to provide immediate care and/or readily contact the necessary personnel.
Benefits

Potential benefits from participation in this study include (1) knowledge of your barbell back squat 1RM (2) safe maximal testing under the professional supervision of a certified strength and conditioning specialist and (3) knowledge of your lifting technique and power output in different footwear. You will also be contributing to research to help understand sex differences in weightlifting and how footwear influences weightlifting.

Confidentiality

The number you will be assigned during your first visit will be identifiable by the researchers only. The corresponding data for each subject participating in this project will be secured in a limited access location. The researcher retains the right to use and publish non-identifiable data. While individual responses are confidential, aggregate data will be presented representing averages or generalizations about the responses as a whole. All data will be stored in a secure location accessible only to the researchers. Upon completion of the study, all information that matches up individual respondents’ names with corresponding data and video recordings will be destroyed, although the unidentifiable data will be maintained on a password-protected computer/server in the Department of Biology at JMU.

Participation & Withdrawal

Your participation is entirely voluntary. You are free to choose not to participate. Should you choose to participate, you can withdraw at any time without consequences of any kind.

Questions about the Study

If you have questions or concerns during the time of your participation in this study, or after its completion or you would like to receive a copy of the final aggregate results of this study, please contact:

Ameera Teal
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James Madison University
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James Madison University
(540) 568-6930
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Christian Carter, Ph.D.
Athletics Department
James Madison University
(540) 568-7903
carte5cr@jmu.edu

Questions about Your Rights as a Research Subject

Dr. David Cockley
Chair, Institutional Review Board
James Madison University
(540) 568-2834
cocklede@jmu.edu

Giving of Consent

Appendix I
I have read this consent form and I understand what is being requested of me as a participant in this study. I freely consent to participate. I have been given satisfactory answers to my questions. The investigator provided me with a copy of this form. I certify that I am at least 18 years of age.

☐ I give consent to be videotaped during my testing session. ________ (initials)

____________________________________
Name of Participant (Printed)

____________________________________   ______________
Name of Participant (Signed)                     Date

____________________________________   ______________
Name of Researcher (Signed)                     Date
AHA/ACSM Health/Fitness Facility Pre-participation Screening Questionnaire

Assess your health status by marking all true statements.

**History**
You have had:
- _____ a heart attack
- _____ heart surgery
- _____ cardiac catheterization
- _____ coronary angioplasty (PTCA)
- _____ pacemaker/implantable cardiac defibrillator/rhythm disturbance
- _____ heart valve disease
- _____ heart failure
- _____ heart transplantation
- _____ congenital heart disease

**Symptoms**
- _____ You experience chest discomfort with exertion
- _____ You experience unreasonable breathlessness
- _____ You experience dizziness, fainting, or blackouts
- _____ You take heart medications

**Other Health Issues**
- _____ You have diabetes
- _____ You have asthma or other lung disease
- _____ You have burning or cramping sensation in your lower legs when walking short distances
- _____ You have musculoskeletal problems that limit your physical activity
- _____ You have concerns about the safety of exercise
- _____ You take prescription medication(s)

**Cardiovascular risk factors**
- _____ You are a man older than 45 years
- _____ You smoke, or quit smoking within the previous 6 months
- _____ Your blood pressure is > 140/90 mmHg
- _____ You do not know your blood pressure
- _____ You take blood pressure medication
- _____ Your blood cholesterol level is > 200 mg/dl
- _____ You do not know your cholesterol level
- _____ You have a close blood relative who had a heart attack or heart surgery before age 55 (father or brother) or age 65 (mother or sister)
- _____ You are physically inactive (i.e. you get < 30 minutes of physical activity on at least 3 days of the week)
- _____ You are > 20 pounds overweight

If you marked any of these statements in this section, consult your physician or other appropriate health care provider before engaging in exercise. You may need to use a facility with a medically qualified staff.

If you marked two or more of the statements in this section, you should consult your physician or other appropriate health care provider before engaging in exercise. You might benefit from using a facility with a professionally qualified exercise staff to guide your exercise program.

You should be able to exercise safely without consulting your physician or other appropriate health care provider in a self-guided program or almost any facility that meets your exercise program needs.

_____ None of the above

Appendix II
Subject Pre Participation Survey

Name: ______________________

Age: ______________________

Biological Sex: _______________

1. How many days per week do you attend a facility designated for exercise and participate in weightlifting?
   a. <2
   b. 2-3
   c. 3-4
   d. 4+

2. How much time do you dedicate to lifting weights during a single session?
   a. 0-30min
   b. 31-45min
   c. 46-60min
   d. 60min+

3. How long have you consistently lifted weights for the duration indicated in Questions 1 and 2?
   a. < 1 month
   b. 1-2 months
   c. 2-3 months
   d. >3 months

4. Do you have experience in the loaded high bar back squat? If yes, how many years’ experience do you have in this exercise?
5. What type of footwear do you regularly lift in when doing the high bar back squat?
   a. Weightlifting shoes
   b. Running shoes
   c. Minimalist shoes (i.e. Nike Free 3.0)
   d. Other (please specify) ________________________

6. From the options listed below, please indicate the footwear you currently own (circle all that apply).
   a. Weightlifting shoes
   b. Running shoes
   c. Minimalist shoes

7. Do you have experience in the high bar back squat lifting in more than one of the footwear listed in question 5? If so which ones?

8. Have you been injured within the past year? If yes please specify what injury occurred, the time it was sustained (i.e. how long ago) and the duration of the injury.

9. What type of footwear do you prefer to wear when weightlifting?

10. What is your shoe size?
References


Appendix IV


Appendix IV


Appendix IV
during a single-limb squat on both a stable and labile surface. *J Strength Cond Res.* 2007;21(1):105-111.
