THESIS

THE EFFECT OF REPETITION ON FORCE PLATFORM METRICS DURING THE

BILATERAL BODYWEIGHT SQUAT

Submitted by

Jillian Rose Sirkis

Graduate Degree Program in Bioengineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2018

Master's Committee:

    Advisor: Raoul F. Reiser II

    Brian L. Tracy
    John C. Rosecrance

ABSTRACT

THE EFFECT OF REPETITION ON FORCE PLATFOROM METRICS DURING THE

BILATERAL BODYWEIGHT SQUAT

INTRODUCTION: Functional Movement Assessments (FMAs) have been gaining popularity for screening athletes to determine weaknesses that could increase risk for injury. A common movement among many FMAs is the bilateral bodyweight (BWT) squat. Currently, FMAs typically require only 3-5 repetitions of the squat when unfatigued. However, it is known that fatigue affects performance and increases injury risk. It is possible that performing more repetitions might simulate the effects of fatigue, increasing the sensitivity of the FMA. PURPOSE: The goal of this investigation was to analyze the vertical ground reaction forces (GRFvs) and center of pressure (CoP) stability metrics during the down phase, up phase and whole movement across the course of a 20 repetition set of the BWT squat in a recreationally competitive group of young adult women. It was hypothesized that on average, due to changes in some individuals, there would be an increase in asymmetries and normalized values from the early repetition ranges to the later repetition ranges of the bilateral BWT squat in the down phase, up phase, and in the whole movement, that there would be evidence of fatigue in the later repetitions, and that the measures would be repeatable from day-to-day. METHODS: Fourteen recreationally active women (mean ± SD age: 20.5 ± 2.1 yrs; height 167.2 ± 7.3 cm; mass 66.9 ± 10.6 kg) with competitive sport backgrounds performed 20 bilateral BWT squats to a thighs parallel to the floor position while force platform data were recorded under each foot. Asymmetries and normalized metrics were compared across the early repetitions (2-7), middle

repetitions (8-13), late repetitions (14-19), and entire set (2-19). Six subjects were reassessed for repeatability. RESULTS: Although not all measures analyzed produced group level changes from the early repetition ranges to the later repetition ranges, there was evidence of some people expressing different force platform metrics in the middle and later repetitions compared to the early repetitions in both GRFv (absolute average GRFv asymmetries during the up phase ($p=0.008$) and whole movement ($p=0.025$), relative minimum GRFv asymmetries during the down phase ($p=0.018$), normalized net minimum GRFv during the up phase ($p = 0.005$)) and CoP (relative AP sway asymmetry during the down phase ($p=0.006$) and whole movement ($p=0.006$), relative AP path length asymmetry during the down phase ($p=0.002$) and whole movement ($p=0.002$), normalized net AP sway ($p=0.031$)). High repeatability (Cronbach's alpha > 0.8) was found in the majority (107 out of 168) of metrics from day-to-day. CONCLUSION: Evidence of change, but limited evidence of fatigue, was found from the early repetition ranges to the later repetition ranges of the BWT squat. Furthermore, the high Cronbach's alpha values show that many of the metrics are repeatable from day to day. Differences also existed in response to repetitions between the up and down phases. Therefore, it is important to further investigate beyond the typical 3-5 repetitions as well as within each phase of the movement in order to determine if greater sensitivity for risk of injury while performing the BWT squat can be obtained.

AKNOWLEDGEMENTS

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Lower extremity injuries are a common occurrence in ground based sports. For example, a study of high school athletes, showed that 15.3% of 780 female and 15.2% of 764 male athletes sustained a lower extremity injury that caused them to miss an average of 7 days (McGuine, 2017). Moreover, these lower extremity injuries are often non-contact related (i.e., no other player is involved), and in fact 85% of anterior cruciate ligament (ACL) injuries of the knee in soccer result from non-contact or indirect contact from other players (Sasaki, 2018). Since the majority of these injuries are non-contact, they are believed to be highly preventable (Myers, 2010). There also appears to be a sex bias with females participating in ground based sports such as soccer, basketball, floorball and handball possessing a three to five times an increased risk of ACL injury compared to their male counterparts (Steffen, 2016).

In an attempt to reduce these preventable injuries, functional movement assessments (FMAs) have been used at the beginning and throughout the athletes' sports season in order to identify potential risk factors for injury. FMAs typically assess individual joint motion, limb motion patterns and control, as well as side-to-side functional asymmetries. A popular FMA to determine athletic injury risk is the Functional Movement Screen (FMS), which is comprised of seven functional movements that are qualitatively rated from 0 to 3, with 0 being the lowest score and 3 the highest score. A score of 0 is given when there is pain during a task or the task cannot be completed. The functional movements include the deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push-up and rotary stability tests and three clearing tests for a shoulder, spinal extension and spinal flexion (Tee, 2016). A composite score of less than 14 purportedly indicates an increased risk for injury in both athletic

and occupational populations (Duke, 2017). FMAs, such as the FMS, have proved to be able to identify some, but not all athletes with greater risks for injury (Duke, 2017).   For example, in a study comparing the pre-season FMS scores with injury during the season for professional American football players, it was found that the FMS was highly specific with a specificity score of 0.91 (95%CI = 0.83-0.96), but not very sensitive with a sensitivity score of 0.54 (95%CI = 0.34-0.68) (Kiesel, 2007). This means that the FMS was very good at predicting injury in those who had a low score, although it did a poor job of predicting all who were injured. In other words, there were too many people that were missed/overlooked by having high scores that did not show a risk for injury.

The bilateral bodyweight (BWT) squat is a popular lower-extremity functional movement that is included in many FMAs. Besides the FMS, it is included in the 9-Test Screening Battery, Modified 4 Movement Screen, Movement Competency Screen, Netball Movement Screening Tool, Athletic Ability Assessment, Conditioning Specific Movement Tasks, 16 Physical Performance Measures Testing Battery and Titleist Performance Institute level 1 (Bennett, 2017). The bilateral BWT squat requires the triple flexion and extension pattern of the hips, knees and ankles (Leal de Souza, 2017) which are involved in not only activities of daily living but also athletic activities such as running, jumping, and landing (O'Reilly, 2017). Since both limbs need to perform the bilateral BWT squat in unison, asymmetries and individual limb weaknesses can be screened (Sanford, 2016). The BWT squat motion is broken down into two parts, the down phase, which is the ankle, knee and hip joints are flexed while being controlled with eccentric muscle contraction and the up phase which these joints extend with work performed by concentric muscle contraction (Leal de Souza, 2017). Eccentric muscle contraction involves the lengthening of the muscle, generally in order to decrease the

acceleration of a load and concentric muscle contraction is the shortening of a muscle to usually increase the acceleration of a load (Munger, 2017).   Since force production and neural control differs in these two forms of contraction, it is important to measure individual phases to find deficits in strength and power within each phase of a movement (Jordan, 2015). The BWT squat has shown promise in injury risk prediction. A study involving Division I collegiate athletes resulted in odds ratios of 1.09 (95% CI = 0.35-3.39) for a score of 1 and 1.14 (95% CI = 0.39-3.32) for a score of 2 for the Deep Squat during the FMS (Warren, 2015). These odds ratios mirror the previous study mentioned about the FMS as a whole in that a large proportion of those with scores of 1 or 2 sustained of injury, although there were many athletes that had a score of 3 that sustained an injury.

One possible reason for predictive limitations in some of the existing FMAs is their reliance on administrator observation and interpretation. When scoring the squat in the FMS the administrator is looking for both asymmetry as well as individual joint and limb attributes. Force platforms are a potential quantitative tool to add to visual cues. Force platforms are a standard tool to not only analyze vertical ground reaction forces (GRFv), but also the motion of the center of pressure (CoP) for balance and stability during the BWT squat and stand-up movements (Ji-Won Kim et al. 2014).   In a study involving athletes that returned to sport after an ACL reconstruction, peak GRFv were reduced in the affected limb, with mean peak forces of 1110 N compared to 1153 N in the unaffected limb (Flanagan, 2008). Since the GRFv was significantly lower in the limb that had a prior injury, reduced peak forces can indicate weakness. The importance of collecting CoP variables is explained in a study where participants had a painful injection in their knees during a quit stance activity. When one knee had the painful injection, medial/lateral (ML) sway towards their knee without the injection increased from 1.0±0.1 to

3

1.5±0.2 cm and when both knees had the painful injection, ML sway increased from 1.1±0.1 to

1.6±0.2, mean anterior/posterior (AP) sway speed increased from 6.5±0.4 to 9.3±1.7 cm/s, and

mean ML sway speed increased from 4.7±0.2 to 5.8±0.6 cm/s, showing that pain increases

postural sway (Hirata, 2012). With two force platforms, GRFv and CoP may be assessed

individually under each foot and therefore, both asymmetries and individual data can be analyzed

for each leg. Data from two force platforms may also be combined to examine the net GRFv and

CoP, similar to if both limbs were measured while on a single platform. While force platforms

have been economically out of reach for many, lesser expensive portable options, to include

pressure sensing pads are now available (Razak, 2012).

FMAs are usually performed with few repetitions and when athletes are not yet fatigued

(Augustsson, 2004). FMAs are often used to determine whether it is safe for a person to

participate in athletic activities (Cook, 2006), and therefore highly fatiguing a person prior to

approving them for athletic activities could put them at risk. Since fatigue is thought to increase

injury risk and decrease performance (Wilke, 2016), and athletes usually sustain non-contact

injuries during the later portion of games and practices (Small, 2009), it is speculated that FMAs

may have improved predictive capabilities if performed while athletes are fatigued. Inducing

fatigue for an FMA in an appropriately controlled manner is a time consuming process (Barber-

Westin, 2017), making it difficult to assess an entire team in an efficient manner. An

increasingly popular alternative to utilizing a controlled fatiguing protocol is having the athletes

play a game before performing an FMA (Jordan, 2016). The downside of using match play to

induce fatigue is the difficulty of standardization of fatigue due to athletes performing at

differing levels during a game and the wait time of the first athlete tested to the last athlete tested

effecting rest and therefore fatigue of the athlete. Without the use of a fatiguing protocol, the

three to five repetitions of the BWT squat might not be demanding enough to expose any limb deficits or asymmetries that an athlete might have. One potential way to safely induce a small level of fatigue is by having athletes perform more repetitions of the BWT squat. Currently, there is no known research that has determined the fatigue potential of this method and how asymmetries might change when more than five BWT squats are performed in succession. However, 20 BWT squat jumps have been studied to determine jump height changes with fatigue. Jordon (2016) found that over the 20 squat jumps, the jump height significantly decreased and therefore, fatigue was evident. Since 20 BWT squat jumps induced fatigue, perhaps increasing the number of BWT squats from 3-5 to 20 could induce fatigue. Therefore, if the athlete performs enough repetitions of the BWT squat, perhaps additional deficits or asymmetries might be uncovered, therefore bringing attention to athletes who would have slipped through the cracks although they are at an increased risk of injury.

Statement of Goals

The goal of this investigation was to determine how asymmetries and individual limb GRFv metrics changed over 20 repetitions of the BWT squat in young and healthy recreationally active women. A secondary goal was to determine the day-to-day repeatability of measures taken during 20 bilateral BWT squats.

Hypothesis

We hypothesized that on average, due to changes in some individuals, there would be an increase in asymmetries and normalized values from the early repetition ranges to the later repetition ranges of the bilateral BWT squat in the down phase, up phase, and in the whole movement. We also hypothesized that evidence of fatigue would exist in later repetitions of the 20 BWT squats and that measures would be highly repeatable from day-to-day. If evidence is

found that additional repetitions might expose unique information not observed in just the first few repetitions, that fatigue is induced, and the measures are repeatable, a more comprehensive follow-up could be performed to see if these changes are similar to what might happen from a more exhausting fatigue protocol. It will also be important to determine if both men and women respond similarly.

CHAPTER II

LITERATURE REVIEW

Introduction

      Non-contact injures are a problem in the work place and in athletics. Currently there are

functional movement assessments (FMAs) designed to screen for injuries in both populations,

although due to increased lower limb injury risk in athletes, the focus on this research will be on

investigating lower limb deficiencies in athletic populations. It is commonly known that lower

limb asymmetries increase risk for lower limb injury and also decrease performance, therefore, it

is important that FMAs include movements that include both lower limbs such as the BWT

squat. Current FMAs are highly predictive for those who score low, although there are a large

proportion of athletes who are injured that receive high scores. Interestingly, FMAs are

performed prior to fatiguing the athlete, although most injuries occur in the later portion of

practice and competition. Therefore, the goal of this literature review will be to examine how the

BWT squat is an integral portion of FMAs and how the BWT squat can highlight asymmetries

and individual limb asymmetries during each of the phases of the BWT squat when female

athletes are fatigued by discussing non-contact injuries, increased ACL injuries in women,

FMAs, the bilateral BWT squat, asymmetries and injury risk, asymmetries and performance,

quantitative analysis of the BWT squat, the phases of the BWT squat and BWT squat and

fatigue.

Non-Contact Injuries

      The National Collegiate Athletic Association (NCAA) has recorded 182,000 injuries in

Division 1(D1) athletes from 1988 through 2003, with 36.8% and 17.7% of injuries in practice

and games, respectively, as non-contact injuries and 53.8% and 53.7% of these injuries in games

and practices, respectively, occurred in the lower extremity (Hootman, Dick and Angel, 2007). Moreover, out of these non-contact injuries, 14.9% were ankle ligament injuries and only 2.6% were ACL injuries (Hootman, Dick and Angel, 2007). Although more recent compiled NCAA data is not readily available, it was found that from 2009 through 2015 in women's D1 lacrosse, out of 142,911 total injuries, 26.0% and 32.1% were non-contact injuries in competitions and practices, respectively, and of those injuries, 7.8% were knee sprains and 41.2% of those knee sprains were severe (Kerr, 2018). Thus, severe knee sprain injuries not only effect many athletes, but the rate has been increasing since 1988. The remaining asymmetries following an ACL repair ultimately increase risk for ACL injury of the non-injured knee by 15 times (Paterno, 2012). In addition to the pain and recovery caused by an ACL injury, those who have undergone ACL reconstruction surgery have over a 50% chance of showing signs of osteoarthritis 10-20 years post-surgery (Jones, 2017). Since non-contact injuries negatively impact so many athletes, it is important to screen for weaknesses to include asymmetries and provide a training intervention in order to decrease injury risk.

ACL Injury Risk in Women

One of the most significant risk factors for an ACL injury is being female, and in fact, females have a 3.8-fold greater risk for an ACL injury than their male counterparts (Numata, 2017). A popular explanation for the increased ACL injury risk in females is due to their low hamstrings to quadriceps strength ratio, which results in reduced ability to stabilize the knee, and during quadriceps contraction, anterior tibial translation occurs, causing the ACL to fail (Behan, 2018). These anatomical differences explain the results of a study where subjects performed drop-landing and cutting tasks. Women in the study produced larger peak GRFv and had smaller knee flexion angle (Miranda, 2013). Thus, the women in the study had less shock absorbing

capabilities in their knees and therefore an increased risk for ACL injury. Furthermore, a study analyzing step-close jumps in both male and female volleyball players, female players showed statistically significant differences in minimum hip, knee and ankle angles between leading and trailing legs with values of 39±8 verses, 90±9, 94±9 verses 92±8 and 65±5 verses 59±5 degrees respectively, whereas males did not have statistically significant differences in minimum hip, knee and ankle angles (Lawson, 2006). The angle asymmetry that is evident in females and not males, could be an explanation as to why females are at an increased risk for ACL injuries. Since females are at an increased risk for an ACL injury, it is important to study females performing functional movements and identify risk factors that would not typically be present in males (Hewett, 1999).

Functional Movement Assessments (FMAs)

Non-contact injuries are seen as preventable (Myers, 2010), and there are current injury risk assessments that screen for injury risk prevention. Although non-contact injury screens are commonly seen in athletics, they are seen in the work place too. According to the United States Occupational Safety and Health Administration (OSHA), the most work related reason for loss of work time is due to musculoskeletal disorders which are defined as illness that affects the muscles, bone, tendons and ligaments and associated blood vessels (OSHA website). Musculoskeletal disorders are seen in construction, industrial, healthcare and office workplaces. Construction work-related musculoskeletal disorders are caused by repetitive motions, awkward postures and lifting weights, resulting in symptoms such as low back pain, neck and shoulder pain, tendonitis and carpal tunnel syndrome (Antwi-Afari, 2017). Industrial workplaces require tasks that are submaximal and repetitive in nature and workers are expected to work through fatigue (McDonald, 2016). Loss of work time due to injury not only physically and financially

affects individuals, but it also affects the productivity and finances of the company. In order to reduce musculoskeletal injury risk, screening tools are used to identify potential injury in the workplace. Bennet reviewed 11 multicomponent musculoskeletal tools which are screening tools that assess movement abilities rather than muscle or joint capabilities (Bennent, 2017). Currently there is no standardized injury screening tool for the workplace, although due to the high incidence of injury there is a need for an effective standardized screening tool (Porru, 2016). The implementation of a standardized screening tool would not only offer clear guidelines for workplaces to screen for injury risk, it would also allow for employees to track injury risk progress through their careers as they change workplaces.

Due to the high numbers of injured National Collegiate Athlete Association (NCAA) athletes, contact injury (i.e., an injury resulting from two or more athletes making contact with one another) prevention has been extensively researched although not much is known about non-contact/overuse injure risks (Warren, 2015). Although, non-contact injuries can be highly preventable and therefore, studying non-contact injuries and methods to screen for and prevent them are necessary. FMAs are now commonly used to screen for weaknesses and asymmetries by evaluating movements such as squats, hops, and jumps, which pertain to most sports. A popular FMA to determine athletic injury risk is the Functional Movement Screen (FMS), which is comprised of seven functional movements that are qualitatively rated from 0 to 3, with 0 being the lowest score and 3 the highest score. A score of 0 is given when there is pain during a task or the task cannot be completed. The functional movements include the deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push-up and rotary stability tests and three clearing tests for a shoulder, spinal extension and spinal flexion (Tee, 2016). A composite score of less than 14 purportedly indicates an increased risk for injury in both athletic

and occupational populations (Duke, 2017). The purpose for the FMS is to assess mobility and stability, identify asymmetries and improper movements (Girard, 2016). Five of the movements in the FMS provide a test for asymmetry by comparing movements laterally (Mokha, 2016). In addition to predicting injury risk, a detected weakness in the kinetic chain via the FMS can determine potential decrease in performance capabilities (Lockie, 1993). Those who have previous injuries, especially athletes who have not fully recovered from injury tend to have lower FMS scores and therefore a higher risk for injury (Duke, 2017).

The allure of the FMS is that it is quick, inexpensive and has a high inter-rater reliability (Girard, 2016). Furthermore, the FMS is very good at predicting injury with those who scored below a composite score of 14 with a specificity score of 0.91 (95%CI = 0.83-0.96), although there are many athletes who score above a composite score of 14 on the FMS, and were injured, therefore the sensitivity score for the FMS is 0.54 (95%CI = 0.34-0.68) (Kiesel, 2007). Specificity is a measure of avoiding false positives whereas, sensitivity measure the avoidance of false negatives and both metrics are rated on a scale of 0.0 to 1.0, with numbers closer to 1.0 preferred. A potential reason as to the lack in correlation between FMS scores and athlete performance is the precision of the scoring system. Since the FMS score of each movement performed properly without pain is rated from one to three, it only has three possible scores which is not precise. A score of two is frequently determined and contains a wider range than one or three, which causes the scoring system to have a lack of discrimination (Hammes, 2016). The variability in the ability of an athlete scored with a two, can cause issue in injury prediction since a score of two is used when there is any compensation during a functional movement (Warren, 2015). Additionally, the correlation between composite scores and injury prediction can be caused by the different movements that athletes perform. In a study performed with

competitive runners, the FMS composite score was not reliable in injury prediction, although separately, each of the individual scores of the deep squat and active straight leg raise were (Bullock, 2016). Since the FMS is comprised of movements involving both upper and lower extremities an athlete involved in a sport that mainly involves the lower extremity could be at a higher risk for a lower limb injury than what the FMS states if they perform well on the upper extremity portion. The composite FMS score could dilute the predicted injury risk of an athlete due to the nature of the athlete's sport, and therefore the FMS composite score has been questioned and should be interpreted as seven individual tests rather than one (Tee, 2016). It is also questioned whether or not the movements reflect the measures of movement, such as the trunk stability push-up, which tests for stability of the spine, although it requires that the athlete also has sufficient upper extremity strength to perform this movement (Willigenbrug, 2017). Additionally, it has been found that FMS scores do not have repeatability in that changes in score without changes in health status or ability can be caused by interpretation of the task instructions, previous experience and motivation (Frost, 2015). Results of a study comparing 11 different FMAs suggests that each of the studied FMAs are limited in their abilities to predict risk of injury and performance, potentially due to their simple scoring methods that have low sensitivity (Bennet, 2017). Although FMAs such as the FMS are good at predicting injury in those that are at extremely high risk, they can be improved upon by catching more individuals that have a reasonable risk for injury that are not identified with the current protocols.

Bilateral Bodyweight Squat

The bilateral BWT squat is a full-body, closed-chain exercise that is comprised of movements that are necessary for activities of daily living and sport, and therefore are a part of most resistance and rehabilitation programs (O'Reilly, 2017) (Severin, 2017)(Mengarelli, 2018).

In fact, the bilateral BWT squat is in the beginning of resistance training programs as a precursor to unilateral exercises (McCurdy, 2005). The BWT squat has a variety of techniques that can affect the range of motion of the subject. In addition to technique, intensity of the BWT squat can be altered by adjusting the number of repetitions or adding an external load (Kellis, 2005). Since anterior shear forces in the knee are relatively low during the squat, it is used in rehabilitation for ACLR, patellofemoral dysfunctions, total joint replacement and ankle instability to increase quadriceps muscle strength (Webster, 2013) (Dionisio, 2008). The bilateral BWT squat requires mobility and stability at the ankle, knee, hip and trunk and is found to be a moderate predictor of the performance of the FMS since those with a combined score of 12 have a 3.56 times increased chance of scoring below a 2 on the deep squat (Clifton, 2015). Since the BWT squat strengthens the ankle, knee and hip extensors, it is used to train athletes to improve performance of sprinting, jumping, throwing and striking skills (Vazquez-Guerrero, 2016). In addition to training, the BWT squat is used in many FMAs. Besides the FMS, it is also used in the 9-Test Screening Battery, Modified 4 Movement Screen, Movement Competency Screen, Netball Movement Screening Tool, Athletic Ability Assessment, Conditioning Specific Movement Tasks, 16 Physical Performance Measures Testing Battery and Titleist Performance Institute level 1 (Bennett, 2017). Each of the muscles around the ankle, knee and hip joints eccentrically contract during flexion (down phase) and concentrically contract during extension (up phase) over the duration of the squat (Leal de Souza, 2017).

Asymmetries and Injury Risk

During the bilateral BWT squat, the lower limbs should move and support the body in unison, which provides as a good screening tool for asymmetries (Sanford, 2016). Asymmetries are defined as lateral differences, most commonly in the extremities, between the left and right

sides of the body. More specifically, functional asymmetries are lateral differences in the

kinetics and/or kinematics of body movement (Girard, 2016). Functional asymmetries are

caused by differences in muscle hypertrophy, muscle strength, flexibility, bone mineral content,

bone mineral density, and neuromuscular control (Filipcic, 2016), (Read, 2016). Functional

asymmetries are affected by genetic, neurological, sociocultural, and life experiences and change

as a person goes through life (Guilherme, 2015). In fact, functional asymmetries have been

observed in humans as early as infants during half-kneel pull to stand and asymmetrical four-

point pattern kneeling and crawling (Atun-Einy, 2016). Furthermore, asymmetries continue to

develop as humans grow and begin to use limbs for more functional tasks such as eating,

walking and reaching and holding items. Upper and lower limbs of the body can have different

asymmetries at varying levels. For instance, about 90% of the human population prefer to use

their right hands whereas only 25-45% prefer to use their right legs (McGrath, 2016).

Asymmetries can change when the cadence of a task is increased, as it has been shown that as

walking pace increases, so do the asymmetries between legs (Radzak, 2017). Asymmetry is

found in healthy populations in activities such as walking, where different legs are primarily

used for stabilization, propulsion or braking (Radzak, 2016). In addition to activities of daily

living, many sports require asymmetric movements and therefore, a development of asymmetries

due to sports is common (Kobayashi, 2010), (Dauty, 2007). For example, fencers have an

increased grip strength in their weapon hand (Roi, 2008). Although healthy populations express

asymmetries, significant asymmetries increase risk for injury, especially in athletic populations

(Filipcic, 2016).   In fact as asymmetries in strength and lean mass increase, so does the injury

incidence, especially when athletes have asymmetries above 10%, their risk for more severe

injuries increases (Hart, 2014). Additionally, leg strength asymmetries have been found in

soccer players and contribute to hamstring injury risk (Lord, 2017). Furthermore, in a study

where subjects performed an unanticipated cutting task, the pre-contact EMG for the dominant

limb occurred before the non-dominant limb, for example, the dominant rectus femoris peaked at

-52.2±36.0% (from -11 to 0%) while the non-dominant peaked at -40.7±32.3%, showing a limb

difference and therefore an increased risk for ACL injury (Greska, 2017). Since asymmetries

have been shown to increase injury risk, especially asymmetries above 10% as explained by

Hart, a 10% asymmetry cut off should be used to determine whether or not an athlete is at risk

for an injury.

Asymmetries and Performance

Asymmetries are commonly known to hinder performance of otherwise symmetric tasks,

such as vertical stiffness asymmetries, which have been found to hinder change of direction

performance in a drop jump test (Maloney, 2017).   Athletes who are more symmetric tend to

perform better in running competitions since, tasks that are performed symmetrically tend to be

more efficient and therefore less physically demanding (Trivers, 2014). Coordination is also

affected by asymmetries. In fact, it was found that in Australian Rules football, those with less

inter-limb asymmetries were able to more accurately kick a ball to a specific position on the field

(Bishop, 2018). Furthermore, in Australian Rules football, those with larger bilateral differences

had a decreased change of direction performance and therefore increased performance rigidity

that could lead to a higher injury risk (Hart, 2013). Since larger asymmetries decrease

performance, it is ideal to address these asymmetries in order to enhance the performance of

athletes. Furthermore, it has been found that during an isometric squat assessment, athletes who

perform the movement more symmetrically tend to outperform those who are less symmetric

(Bailey, 2015). Furthermore, it was found that performance on a maximal squat test was a good

predictor of the counter movement jump in young soccer players, which shows that squats are good for predicting other functional movements (Bridgeman, 2018). For instance, in more asymmetric individuals, the correlation of average GRFv asymmetry between the single leg drop landing and the BWT squat was 0.631 for more asymmetric individuals (Overmoyer, 2013). Since the BWT squat is safe and used for rehabilitation and screening for asymmetries and it is predictive of performance on other functional movements, it could be a useful tool to assess an athlete's abilities as they are going through a rehabilitation process to return to sport or to assess the risk of injury to healthy athletes.

Quantitative Analysis of the Bodyweight Squat

As determined above, that the composite score of the FMS is useful at predicting injury in lower scores, although many athletes with high composite scores ended up sustaining an injury, it was found that similar injury prediction occurred for the deep squat individual movement score as exposed by Warren et al. A study analyzing FMS scores and non-contact injury during the sports seasons of DI collegiate athletes showed that for the deep squat, the odds ratio for a score of 1 was 1.09 with a 95% confidence interval of 0.35-3.39 and the odds ratio for a score of 2 was 1.14 with a confidence 95% interval of 0.39-3.32 (Warren, 2015). Since each of the odds ratios are larger than 1, it means that the deep squat score of 1 or 2 had good odds of predicting injury, although the odds of predicting an injury in all scores were low since there were many athletes who were scored with a 3 that were injured. A potential reason for predictive limitations within some current FMAs is that they are reliant on administrator observation and interpretation. In order to enhance the visual analyzation of functional movements, force platforms can be used as an objective, quantitative tool. Furthermore, force platforms are a useful tool to analyze mean, minimum, and maximum GRFv along with the motion of center of

pressure (CoP) for balance and stability during the BWT squat and sit to stand movements (Kim, 2014). With the use of two force platforms, individual leg GRFv and CoP data can be analyzed and asymmetries can also be assessed. CoP variables such as Anterior-Posterior (AP) and Medial-Lateral (ML) sway and path length are important measures to collect in addition to GRFv variables because they determine postural sway during the BWT squat. GRFv data can provide information on weaknesses in limbs. For example, in a study involving ACL replacement athletes that returned to sport, peak GFRv were reduced in the affected limb, with mean peak forces of 1110 N compared to 1153 N in the unaffected limb (Flanagan, 2008). Since the GRFv was significantly lower in the limb that had a prior injury, reduced peak forces can indicate weakness. The importance of collecting CoP variables is explained in a study where participants had a painful injection in their knees during a quit stance activity. When one knee had the painful injection, ML sway towards their knee without the injection increased from 1.0 ± 0.1 to 1.5 ± 0.2 cm and when both knees had the painful injection, ML sway increased from 1.1 ± 0.1 to 1.6 ± 0.2, mean AP sway speed increased from 6.5 ± 0.4 to 9.3 ± 1.7 cm/s, and mean ML sway speed increased from 4.7 ± 0.2 to 5.8 ± 0.6 cm/s, showing that pain increases postural sway (Hirata, 2011). Furthermore, in a study comparing quiet stance CoP sway area before and after fatigue, it was found that in young adults, there was a 46% increase in CoP sway area after the fatiguing protocol (Bisson, 2014). Thus, CoP variables could indicate fatigue, though there is no direct evidence reported on the BWT squat. While force platforms have been economically out of reach for many, lesser expensive and portable options, to include pressure-sensing pads, are now available (Razak, 2012). This widens the population that would be able to use this quantitative information and screen for asymmetries and limb deficiencies on the field, rather than being constrained to visiting a lab or solely relying on visual observation.

Phases of the Bodyweight Squat

The BWT squat motion is broken down into two parts, the down phase, where the ankle, knee and hip joints are flexed while being controlled with eccentric muscle contraction and the up phase where these joints extend with work performed by concentric muscle contraction (Leal de Souza, 2017). During the down phase of the BWT squat, the GRFv decreases as the person's body begins to move towards the ground and then the ground reaction forces begin to increase as the muscles around the hip, knee and ankle eccentrically contract to control the movement and decelerate the person so they do not fall to the ground. The up phase of the BWT squat requires an increase in GRFv above BWT at the start in order reverse the direction of the motion of the body and accelerate it upwards against the direction of gravity. However, it then decreases as the person decelerates into the upright standing position. In both phases as well as overall the mean net GRFv (sum of the GRFv under each foot) will equal the person's BWT For the same level of activation, eccentric muscle contraction produce larger forces than concentric muscle contractions (Bridgeman, 2018). In addition to peak force and neural activation differences, eccentric muscle contraction and concentric muscle contraction differ in their metabolic energy cost, and induction of muscle damage (Gillies, 2006). During quadriceps training that involves both concentric and eccentric muscle contractions with both beginning and ending at rest, the same absolute load is applied for each of the contractions, although the maximum force that could be generated is greater in eccentric than concentric muscle contraction and therefore, the relative workload is smaller for the eccentric muscle contractions (Friedmann-Bette, 2010). Since eccentric muscle contractions and concentric muscle contractions vary from each other, testing both contractions in a functional movement screen is ideal. Many sports require both eccentric and concentric movements, therefore, it is important to measure individual phases to

find deficits in strength and power within each of the eccentric and concentric phases (Jordan, 2015). Furthermore, Jordan et al. found that the kinetic impulse symmetry index was significantly higher in subjects who have had an ACL injury (6.8%) than healthy subjects (0.5%) during the concentric phase of the countermovement jump, whereas there were no statistically significant differences between the subjects who have had an ACL injury (5.2%) than healthy subjects (1.0%) during the eccentric phase of the countermovement jump. Moreover, in a study that tested eccentric knee extensor strength, it was found that those who had a larger bilateral knee extensor strength asymmetry had a higher risk of sustaining an injury and the leg that was injured was significantly weaker than the contralateral leg (Bourne, 2015). Since eccentric and concentric muscle contractions produce can produce different performance deficits and injury risks, measuring both the eccentric and concentric phases of the BWT squat may help to not only increase determination of injury risk, but to also determine what type of muscle contractions need to be improved upon to increase performance and decrease injury risk.

Bodyweight Squat and Fatigue

As discussed above, the BWT squat is a good functional movement that is part of many FMAs. FMAs are usually performed with few repetitions and when athletes are not yet fatigued (Augustsson, 2006). Neuromuscular fatigue and/or the reduction of maximal voluntary force by muscle groups or an individual muscle causes altered lower limb kinematics due to improper muscle activation patterns (Weeks, 2015). Furthermore, muscular fatigue causes the inability to produce energy around a joint by the neuromuscular system (Mate-Munoz, 2017). Fatigue increases the risk for lower limb injury by decreasing coordination and muscle shock-absorbing capacity (Haddas, 2017) (James, 2010). From the beginning of exercise, the capacity to generate maximal force decreases, and therefore fatigue begins once the exercise starts (Byrne, 2002).

Athletes that are fatigued are more prone to injury and are observed to have limb landing

kinematics that result with increased ACL loading (Jordan, 2016) (Bell, 2016). During a loaded

fatiguing squat protocol, those who were considered more symmetric at the start of the

movements did not experience changes in their symmetries or became slightly more symmetric

(Hodges, 2011). Similarly, athletes who returned to sports after an ACL injury, show

asymmetries in their movements, although their movements become more symmetric as they

fatigue (Jordan, 2016), (Webster 2013). Furthermore, during repeated treadmill sprints, it was

found that both legs fatigued at the same rate, and there was no evidence differing levels of

fatigue between legs with asymmetry (Girard, 2016). In addition, it was found that as stroke rate

increased in swimmers, resulting in increased intensity, both the power and recovery phases of

the stroke decreased in asymmetry (Barden, 2011). In contrast, one would assume that

asymmetries would increase as athletes fatigue since asymmetries increase the risk of injury and

most athletic injuries occur towards the end of activities when the athlete is more fatigued (Lessi,

2015). Additionally, it was found that knee internal rotation excursion and knee stiffness

increased in asymmetry from rested running to fatiguing running tasks (Radzak, 2017).

Although some prior research suggests that asymmetries decrease with fatigue, Lessi and Radzak

indicate that fatigue could affect asymmetries, so it is important to determine whether or not

fatigue is a factor in asymmetries and if so, how fatigue affects asymmetries. It is speculated that

fatigue was not found in some of these studies since the subjects were only assessed at maximum

fatigue, and perhaps asymmetries would be found at a moderately fatigued level (Webster,

2015). The tasks performed may also not have lent themselves to express increased fatigue. For

example, Hodges et al (2011) may not have observed increased fatigue in their barbell back squat

protocol due to the need to protect balance and minimize the risk for falling with a heavy load on

their back. Furthermore, even if asymmetries may not change with fatigue, normalized values such as maximum/minimum GRFv and CoP postural sway values may increase, as explained earlier.

FMAs are often used to determine whether it is safe for a person to participate in athletic activities (Cook, 2006), and therefore highly fatiguing a person prior to approving them for athletic activities could put them at risk. Since fatigue is thought to increase injury risk and decrease performance (Wilke, 2016), and athletes usually sustain non-contact injuries during the later portion of games and practices (Small, 2009), it is speculated that FMAs may have improved predictive capabilities if performed while athletes are fatigued (Augustsson, 2006). Inducing fatigue for an FMA in an appropriately controlled manner is a time consuming process (Barber-Westin, 2017), making it difficult to assess an entire team in an efficient manner. An increasingly popular alternative to utilizing a controlled fatiguing protocol is having the athletes play a game before performing an FMA (Jordan, 2016). The downside of using match play to induce fatigue is the difficulty of standardization of fatigue due to athletes performing at differing levels during a game and the wait time of the first athlete tested to the last athlete tested effecting rest and therefore fatigue of the athlete. Without the use of a fatiguing protocol, the three to five repetitions of the BWT squat might not be demanding enough to expose any limb deficits or asymmetries that an athlete might have. Currently, there is no known research that has determined how asymmetries change during multiple BWT squats, although 20 BWT squat jumps have been studied to determine jump height changes with fatigue found that over the 20 squat jumps, the jump height significantly decreased and therefore, fatigue was evident over the 20 squat jumps (Jordan, 2016). Since 20 BWT squat jumps induced fatigue, perhaps increasing the number of BWT squats from 3 to 5 to 20 could induce some short-term fatigue. Therefore, if

the athlete performs enough repetitions of the BWT squat, perhaps potential deficits or asymmetries might be uncovered, therefore bringing attention to athletes are that are at an increased risk of injury who would have slipped through the cracks in a current FMA.

Summary/Conclusion

As previously discussed, non-contact lower limb injuries negatively impact many athletes although they are preventable. ACL injuries are common non-contact injuries that affect athletes, and unfortunately female athletes are at a more increased risk than their male counterparts. FMAs show promise in assessing injury risk, although there are many individuals who are still injured even with these assessments. The bilateral BWT squat is a popular movement in many FMAs due to its triple flexion, extension pattern which is included in many athletic activities such as running and jumping. Furthermore, the BWT squat requires both limbs to move simultaneously, so individual limb deficiencies and asymmetries can be assessed with the bilateral BWT squat. The BWT squat also includes both eccentric and concentric contractions, therefore it has the ability to screen for injury risk in both parts of the movement. Although FMAs and the BWT squat has shown promise in identifying those with an increased risk for lower limb injury, there are many athletes that are identified as having a low risk, yet sustain injuries during the season. The current rating system with limited scoring options along with interrater reliability could be an explanation for the number of athletes at high risk of injury who are missed. Force platforms or more inexpensive and portable options such as pressure sensing mats could be used to aid visual cues in detecting limb weakness or asymmetries. Additionally, although athletes tend to sustain injuries while fatigued, FMAs do not test the athlete under a fatigued state, so by assessing athletes while fatigued, potential weaknesses and asymmetries could be uncovered. The use of fatiguing protocols can be used prior to FMAs to

assess for injury risk while the athlete is fatigued, although these tend to be time consuming. Alternatively, multiple repetitions of the BWT squat can be measured in order to potentially induce fatigue. The goals of the study are to assess GRFv and CoP measures during the up phase, down phase, and whole movement of the BWT squat over 20 repetitions and identify potential changes in normalized and asymmetry values, while also assessing day-to-day repeatability. It is hypothesized that there will be evidence of fatigue from the earlier squat repetitions to the later squat repetitions and that in some subjects, there will be changes in normalized and asymmetry values with increasing squat repetitions and the metrics will show high repeatability.

CHAPTER III

MATERIALS AND METHODS

Experimental Approach to the Problem

To accomplish the goals of this investigation, a cross-sectional research design was used and approved by the Colorado State University Institutional Review Board (Appendix A). Subjects provided written informed consent, health/activity history, and visited the lab a maximum of two times for approximately one hour per visit. The first visit consisted of verification of eligibility, warm-up, anthropometric measurements, hamstring flexibility, and familiarization and performance of six functional movements. The functional movements were tested while collecting force platform data under each foot of the participants. In order, these functional movements included bilateral quiet stance, unilateral quiet stance on each leg, bilateral BWT squats, bilateral maximal hops, bilateral maximal jumps and unilateral posterior chain strength on each leg. The subjects were given three minutes of rest between each functional movement and stretching was not allowed during the duration of the visit. Those who returned for a second visit repeated the protocol of the first visit. After the first data collection, a whole-body Dual-energy x-ray absorptiometry (DEXA) scan was performed on most subjects. Only the bilateral BWT squats were assessed in the thesis. 20 repetitions of the squat were performed in a single set. Differences in GRFv and CoP metrics were assessed between the initial, middle, and late repetitions. Additionally, Cronbach's alpha was used to determine day-to-day repeatability.

Subjects

Fourteen healthy female subjects, ages 18-30 years recruited from the Colorado State University campus, were studied and identified as recreationally active and participated in squatting, hopping and jumping tasks (i.e. hockey, soccer, resistance training, etc.) at least twice

per week in the last four weeks. Subjects were currently competing at the club or equivalent level. Exclusion criteria included self-reported pain, injury or soreness of the back or lower extremities during the time of the visit. All participants with prior injuries were required to have been cleared for athletic participation and performed pain and injury free for at least four weeks prior to participating in the study. Those who had scoliosis before or during the time of data collection were excluded along with those who use a knee, ankle brace or orthotics during squatting, hopping and jumping exercises. Additionally, women who were pregnant at the time of the study were also excluded. Two subjects were excluded during the health history report data collection due to one subject that did not meet the squatting and hopping activity requirements and one subject that wore a knee brace on one leg during squatting and hopping activities.

Procedures

Prior to participation, subjects were contacted by phone or met in person to complete a brief health history and activity questionnaire (Appendix B). After determining the eligibility of the subject the first visit was scheduled. Each subject came to the lab for one visit lasting one hour. After the first visit subjects were asked if they were willing to return between 2-14 days to repeat the protocol. Subjects were also asked to complete an optional 30 minute DEXA scan. Subjects were instructed to abstain from heavy exercise of the lower limbs and back 24 hours before each visit as well as from exercise the day of each visit. Additionally, caffeine consumption was limited to normal daily intake the day of the visit.

At the beginning of each lab visit, eligibility of subjects was confirmed by discussing any pain or change in health status since completing the health history and activity questionnaire. Throwing arm and kicking leg were recorded, along with a description of shoes that the subject

was wearing. If not already obtained, the subjects provided written Colorado State University

approved informed consent (Appendix C) followed by a five-minute warm-up on an upright

stationary cycle ergometer. Subjects were instructed to not stretch at any point during the study

so that one side was not stretched more than another possibly affecting asymmetries, though

additional warm-up and movement practice was allowed. After the warm-up, standing height

and weight were obtained. This was followed by a collection of hamstring range of motion

(modified Thomas Test (Berryman Reese and Bandy, 2002)) and anatomical leg lengths as

described by Evans (1994).

After the anthropometric measurements were recorded, subjects performed functional

movements on two force platforms (Bertec 4060-10, Columbus, OH) mounted side-by-side and

flush with the surrounding floor. Before each functional movement, subjects were instructed on

how to perform each movement and given ample practice. Subjects wore their own athletic

shoes during all movements, except for the posterior chain test where they were in stocking feet.

Subjects wore their own clothing suitable for exercise. One 60 second bilateral quiet stance trial

was performed first followed by four unilateral quiet stance trials (2 on each foot) unless a repeat

was deemed necessary.

The subjects were then given three minutes rest and were introduced to the bilateral BWT

squats movement. A horizontal bar supported by two uprights was placed behind the subject

while standing with one foot on each force platform. The subject was then instructed to hold

both arms straight out in front of them and keep their head facing forward and squat to a position

where their thighs were parallel with the floor. The research assistants verbally instructed the

subjects to raise or lower themselves so that they were in the correct position and the horizontal

bar was placed so that their gluteus maximus would just touch the bar. If the subjects were

unable to reach a thighs parallel position, the bar was raised to the position that the subjects

could squat to. Bar height was then recorded. The squat had a two-second down phase, where

the subjects were to touch the horizontal pole with their gluteus maximus at the end of the two-

second phase (Figure 3.1). This was followed by a two-second up phase where the subject's legs

would be fully extended in a standing position at the end of the phase. Finally, the subject would

stand as still as possible during a two-second pause phase. A recording that repeated the line

"down, down, up, up, pause, pause" for each BWT squat was used so that each subject

performed squats at the same cadence. The subjects then practiced 10 squats with the recording

while the research assistant verbally coached and encouraged the subjects. Stance width was

recorded by placing tape on the force platform anteriorly to the first digit on each foot and

measuring the distance between the two pieces of tape with measuring tape. The subjects were

given about a minute rest and performed 20 BWT squats with the coaching of the recording and

the research assistant. The subject's arms were held horizontally, directly in front of the subject

during the entire trial. After the end of the trial, the horizontal bar and upright supports were

removed from behind the force platforms and the subjects were given three minutes rest.

The subjects finished the visit by performing 20 maximal bilateral vertical hops, 20

maximal vertical jumps, and unilateral posterior chain strength.

Following the completion of the first data collection, subjects participated in an optional

DEXA scan and/or a second laboratory visit where they repeated the tasks of the first visit.

Data Processing and Analyses

Force platform measures for the bilateral BWT squats were sampled at 200 Hz and post

processed in MatLab (MathWorks, Natic, MA). The raw GRFv data were low-pass filtered at 10

Hz with a 4th-order recursive Butterworth filter to remove noise. Besides the individual foot

GRFv, the net GRFv was calculated by adding the two together. Each of the 20 squats were

divided into two parts; the up phase (UP), and down phase (DP) (Figure 3.1). The whole rep

(WR) was also analyzed. The start of each squat was determined when the net GRFv dropped

below the subject's BWT and the end was determined when the net GRFv returned back to BWT

at the end of the up phase. The UP transitioned from the DP when the velocity of the center of

mass reached zero, as determined through the impulse-momentum relationship. For each of the

20 squats, average, maximum and minimum GRFv, along with CoP postural control variables

such as Anterior-Posterior (AP) and Medial-Lateral (ML) Sway and Path Length were calculated

for each leg during each of the phases and WR of all 20 squats. Sway variables were calculated

by subtracting the minimum from the maximum CoP value. CoP postural control variables were

also calculated for the net CoP. Squat repetition ranges were broken into 4 ranges, early (reps 2-

7), middle (reps 8-13), late (reps 14-19) and entire (reps 2-19) and values for each variable were

averaged over each range (Figure 3.2). Normalized values were calculated by dividing GRFv

and CoP variables by each of the subjects' BWT and heights, respectively, and therefore are

presented as % BWT and % height. Relative asymmetries were calculated as Percent Symmetry

Index (%SI, Equation 1) based on dominant (D) and non-dominant (ND) limbs. In this equation,

a positive %SI indicates a greater value on the D (preferred kicking) limb. Absolute levels of

asymmetries were also examined (|%SI|).

Statistical Analyses

Means and standard deviations were calculated for anthropometric and biomechanical

data, including GRFv and CoP variables and higher level comparisons were made for the

biomechanical data. Extreme outliers, which were considered to be three interquartile ranges

away from the upper quartile, were removed and normal distributions were verified by assessing

skewness and kurtosis before performing 1x4 repeated measures ANOVAs to determine

significant main effects between the early, middle, late and entire squat repetition ranges for each

normalized and asymmetry variable. Bonferroni post-hocs were used to explore significant main

effects for comparisons between squat repetition ranges. Furthermore, individual subject data

was plotted for each of the %SI and |%SI| variables during the whole movement, up phase and,

down phase across each of the repetition ranges. Cronbach's alpha was used to determine

repeatability between the two visits. International Business Machines (IBM) Statistical Package

for the Social Sciences (SPSS) (Armonk, NY) was used for all statistics with $\alpha=0.05$ set for

significance.
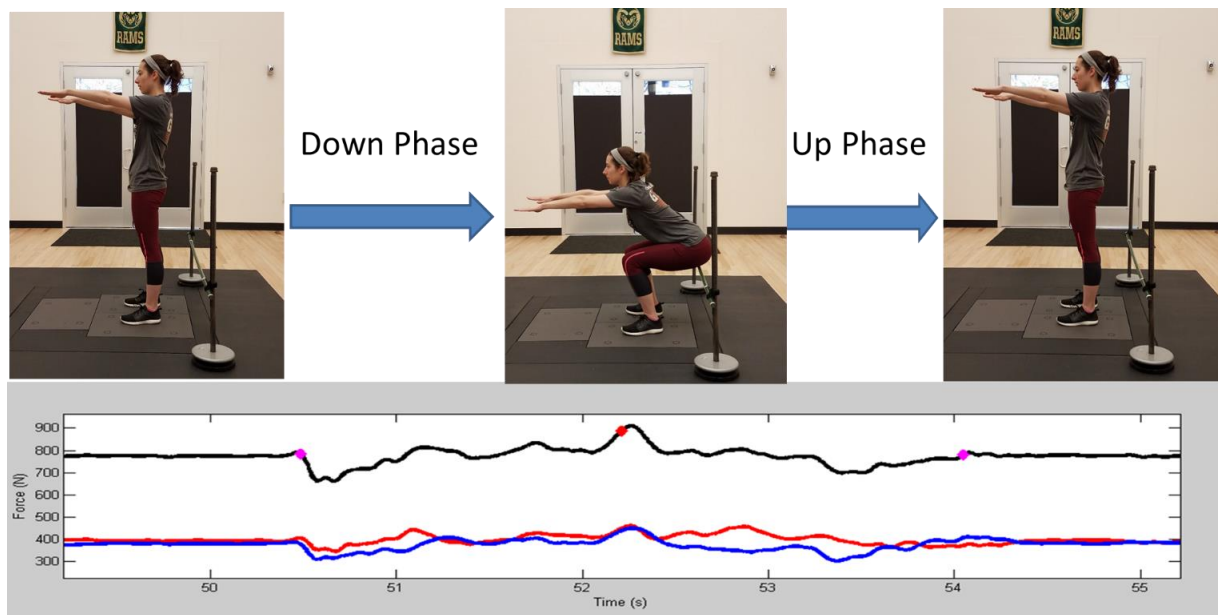
Figure 3.1: Subject performing BWT squat with arms out in front, head facing forward and thighs parallel to the ground. Sample net (black), right (red), and left (blue) GRFv shown during a single repetition of the BWT squat. The pink dots represent the start and end of the movement, while the red dot represents the bottom of the squat when the subject's gluteus maximus touches the green pole.
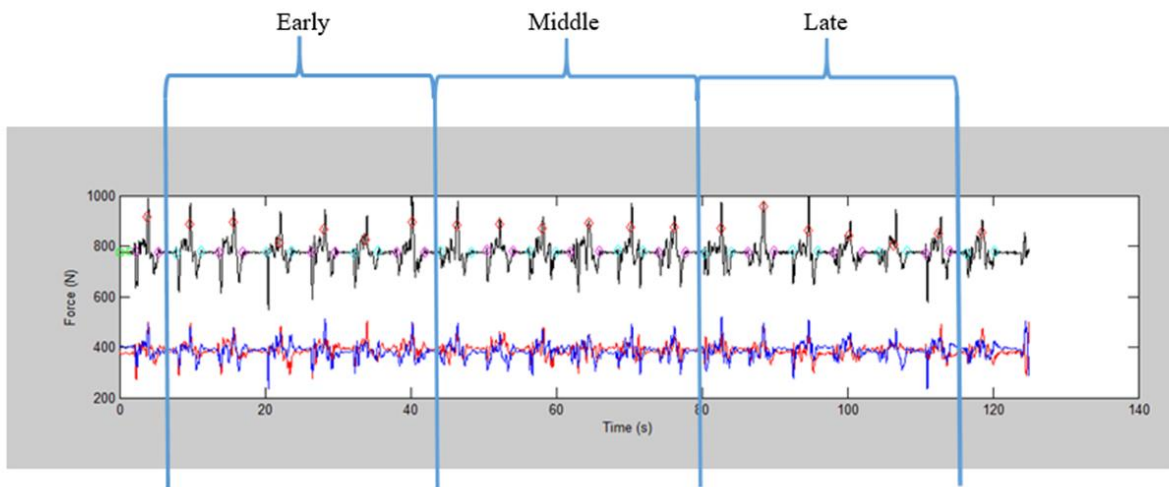
Figure 3.2: Sample net (black), right (red), and left (blue) GRFv shown over 20 bilateral BWT squat repetitions divided by early, middle and late repetition ranges.

$$\%SI = \frac{D\text{-}ND}{\frac{1}{2}(D+ND)} *100 \qquad \text{(Equation 1)}$$

CHAPTER IV

RESULTS

Subject Characteristics

Fourteen female subjects meeting the outlined criteria volunteered, completed the data

collection, and are included in the analysis (Table 4.1) with 6 of them returning for a second visit

to assess repeatability. Of the 14 subjects, only one was not currently competing at the club

sports level, although she was currently competing at the recreational sports level. Additionally,

each of the subjects were competitive through high school, although not all subjects were

competitive in the same sport that they participated in during high school. Each subject reported

their right arm as their preferred (dominant) throwing arm, and all but one subject reported their

right leg as their preferred (dominant) kicking leg. Outliers were minimal with most variables

having 14 subjects in the analysis. Never was more than three subjects removed.

Table 4.1: General Subject Characteristics

	Mean	SD
Age (yr)	20.5	(2.1)
Height (cm)	167.2	(7.3)
Mass (kg)	66.9	(10.6)

Average GRFv

During the whole movement of the first visit, only 2 of the 14 subjects put more weight

on their non-dominant limb over the 20 rep set. Additionally, only 1 subject switched sides of

force dominance from one rep range to another (Figure 4.1). Of those that switched, the highest

|%SI| over the entire set was 0.4 %. Using 10% asymmetry as the threshold for increased injury

risk, 2 subjects were below this threshold in the early reps and then moved above it in the

ensuing rep ranges over the whole movement. One subject was above 10% in the early reps, but

then dropped below in the ensuing rep ranges. Furthermore, during the down phase of the first

visit, only 2 of the 14 subjects put more weight on their non-dominant limb over the 20 rep set,

and only 1 subject switched sides of force dominance form one rep range to another (Figure 4.2).

Using the 10% asymmetry as the threshold for increased injury risk, 1 subject was below this

threshold in the early reps and then moved above it in the ensuing rep ranges over the down

phase. One subject was above 10% in the early reps, but then dropped below in the ensuing rep

ranges. During the up phase of the first visit, only 2 of the 14 subjects put more weight on their

non-dominant limb over the 20 rep set, and only 1 subject switched sides of force dominance

from one rep range to another (Figure 4.3). Using the 10% asymmetry as the threshold for

increased injury risk, 4 subjects were below this threshold in the early reps and then moved

above it in the ensuing rep ranges over the up phase. One subject was above the 10% in the early

reps, but then dropped below in the middle reps and returned back above the 10% in the late

reps.
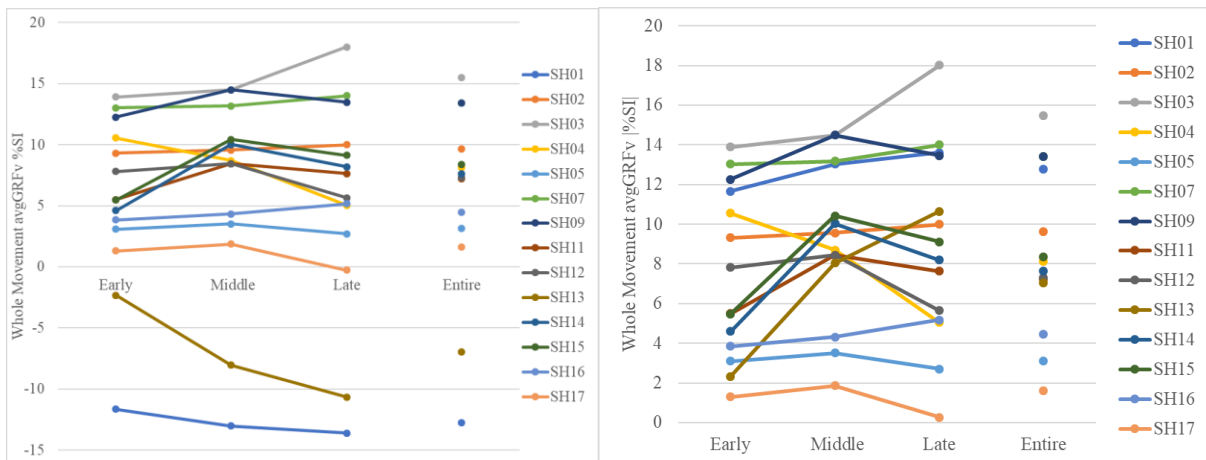
Figure 4.1: Individual average GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges over the whole movement.
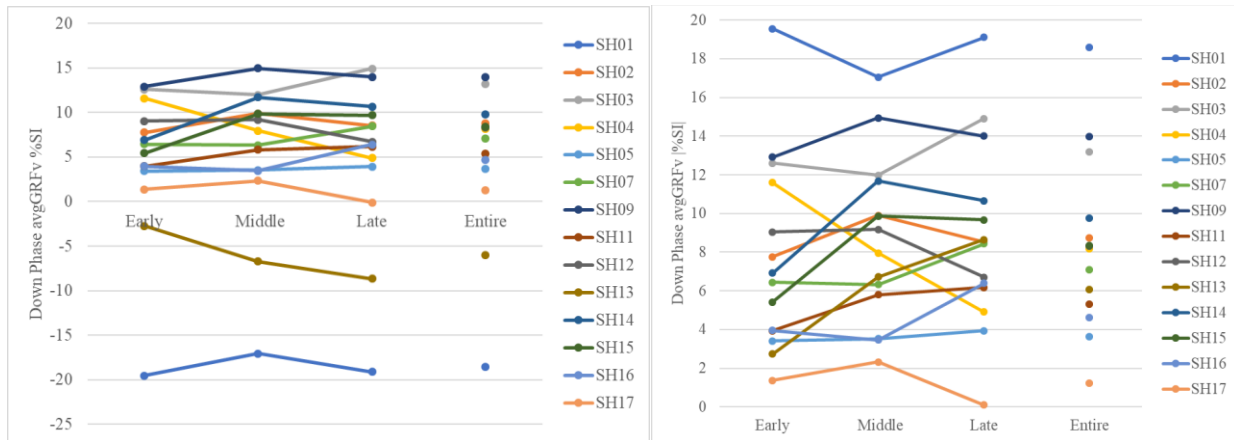
Figure 4.2: Individual average GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges over the down phase.
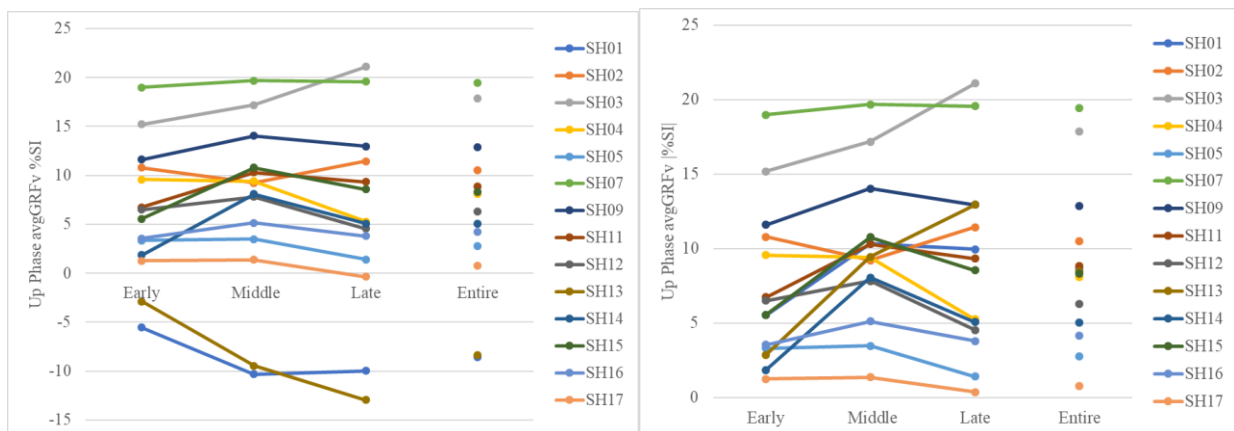

Figure 4.3: Individual average GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges over the up phase.

There were no significant differences in the average GRFv %SI (Figure 4.4) across the rep ranges in either the whole movement or in the up or down phases for the group ($p >= 0.429$). However, there were changes in the average GRFv |%SI| during the up phase ($p=0.008$). Post hocs on the up phase indicated average GRFv |%SI| increased from the early to middle and decreased from middle to entire repetition ranges (Figure 4.5). Additionally, there were changes in the average GRFv |%SI| of the whole rep ($p=0.025$) though the conservative Bonferroni post hocs only suggested approaching significance ($0.050<p<0.100$) with an increase from the early to middle repetition ranges of the whole rep (Figure 4.5).
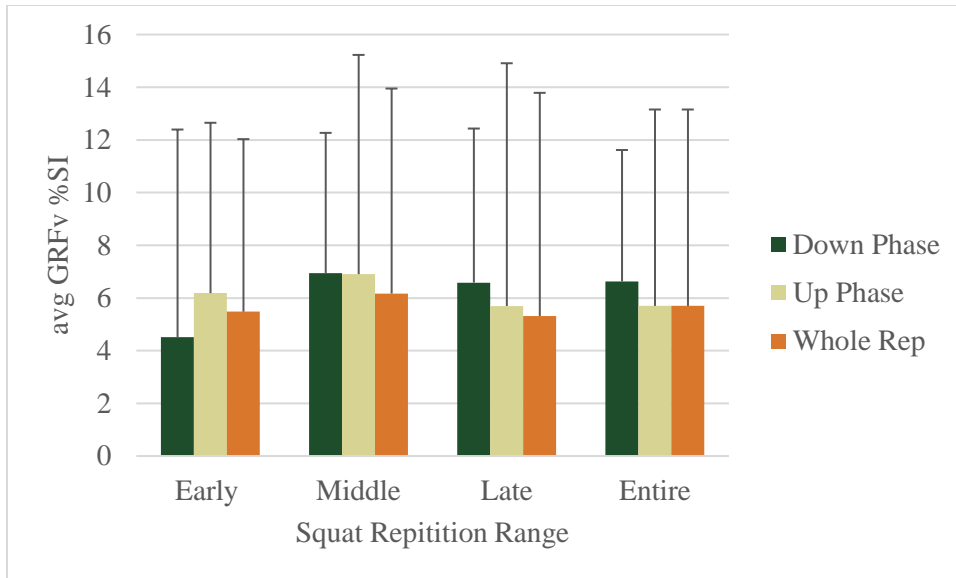
33

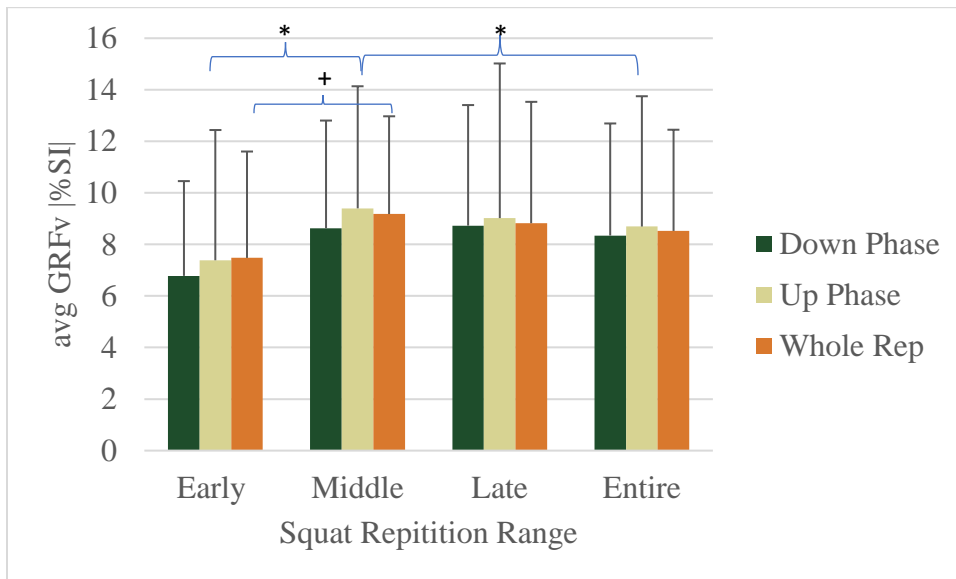Figure 4.4: Mean (+ 1 SD) average GRFv %SI during the BWT squat. No statistical main effects existed (p>0.050).

Figure 4.5: Mean (+ 1 SD) average GRFv |%SI| during the BWT squat. * Indicates a statistically significant difference (p<0.050), + indicates approaching statistical significance (0.050<p<0.100).

The average GRFv %SI showed good repeatability during each of the phases across all repitition ranges with Cronbach's alpha values >= 0.855 (Table 4.2).

Table 4.2: Repeatability Assessment of Average GRFv %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.868	0.918	0.938	0.918
Down Phase	0.895	0.945	0.978	0.950
Up Phase	0.855	0.876	0.909	0.899

Maximum GRFv

During the whole movement only 2 of the 14 subjects had a larger peak instantaneous value on their non-dominant limb over the 20 rep set. Additionally, only 1 subject switched sides of force dominance from one rep range to another (Figure 4.6). Using the 10% asymmetry as the threshold for increased injury risk, one subject crossed the 10% asymmetry threshold after the initial reps, however two others dropped from above to below the threshold over the whole movement (Figure 4.6). Furthermore, only 2 of the 14 subjects had a larger peak instantaneous value on their non-dominant limb over the 20 rep set during the down phase (Figure 4.7). During the down phase, one subject crossed the 10% asymmetry threshold after the initial reps, however one subject dropped from above to below the threshold (Figure 4.7). Moreover, only 2 of the 14 subjects had a larger peak instantaneous value on their non-dominant limb over the 20 rep set and only 2 subjects switched sides of force dominance from one rep range to another during the up phase (Figure 4.8). One subject crossed the 10% asymmetry threshold after the initial reps, however one subject dropped from above to below the threshold during the up phase (Figure 4.8). There were no statistically significant differences in the maximum GRFv %SI (Figure 4.9) or maximum GRFv |%SI| (Figure 4.10) variables ($p \geq 0.286$) during the whole movement, down phase and up phase across each repetition range. There were no statically significant differences in the net maximum GRFv (Figure 4.11) variables ($p \geq 0.252$) during the whole movement, down phase and up phase across each repetition range.
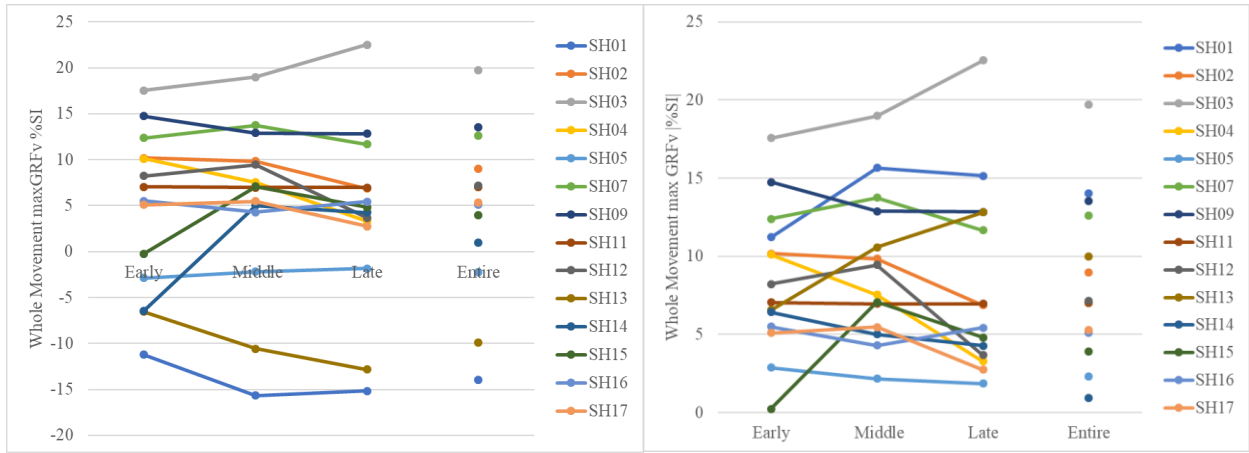
Figure 4.6: Individual maximum GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the whole movement.
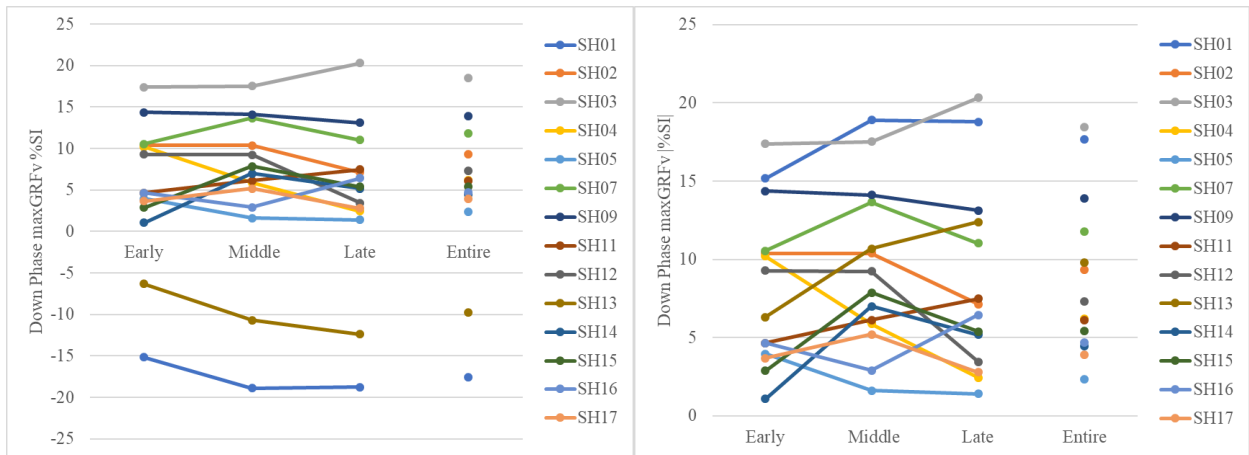

Figure 4.7: Individual maximum GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
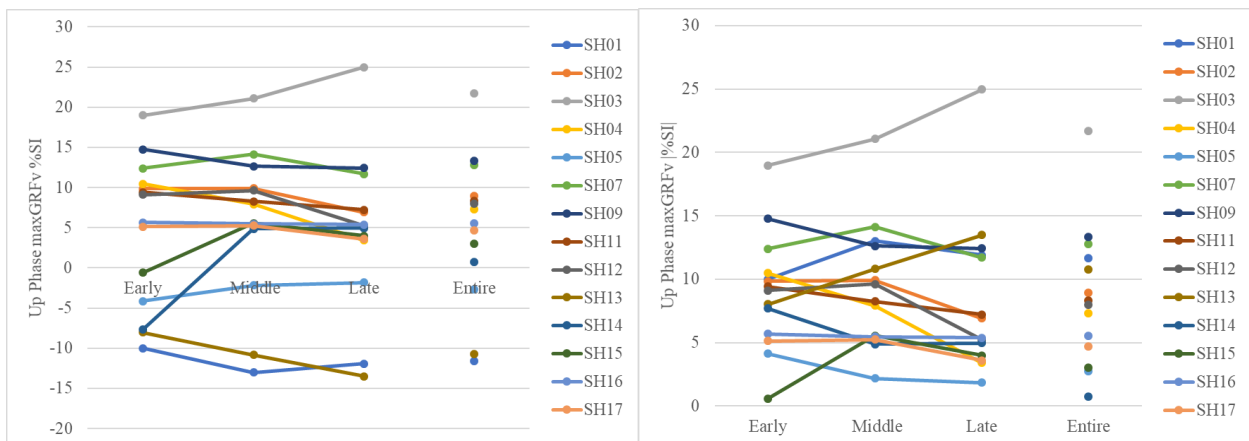

Figure 4.8: Individual maximum GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the up phase.
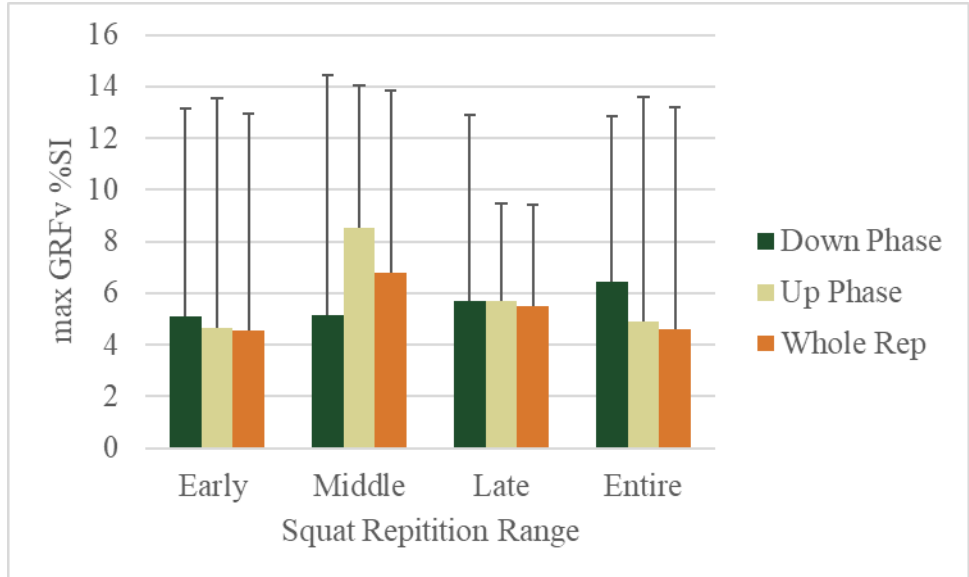
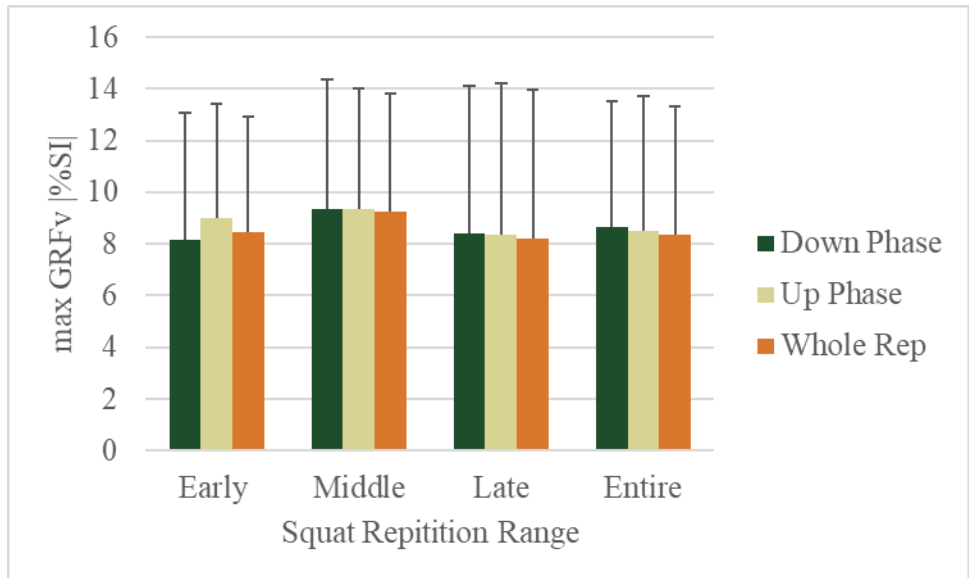Figure 4.9: Mean (+ 1 SD) maximum GRFv %SI during the BWT squat. No statistical main effects existed (p>0.050).

Figure 4.10: Mean (+ 1 SD) maximum GRFv |%SI| during the BWT squat. No statistical main effects existed (p>0.050).

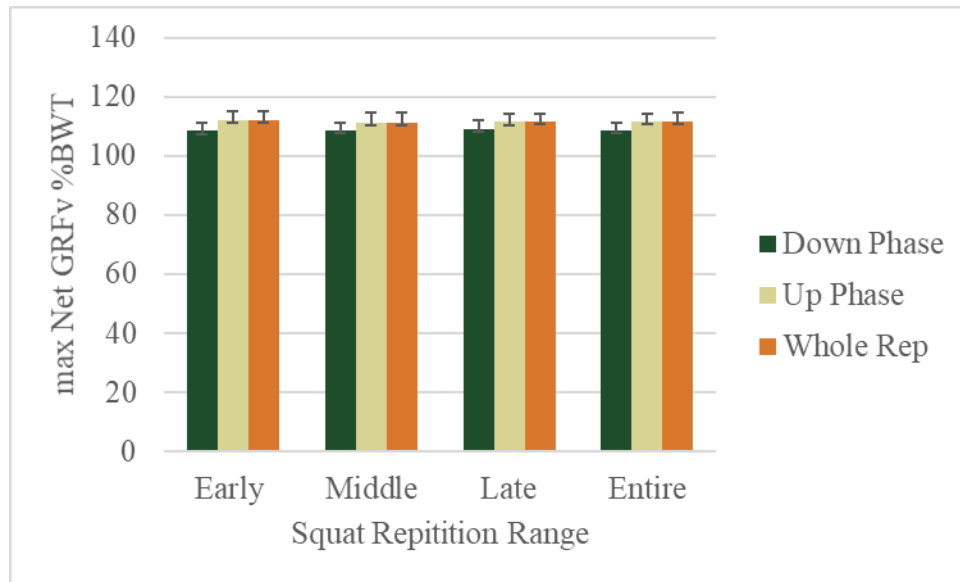Figure 4.11: Mean (+ 1 SD) maximum net GRFv %BWT during the BWT squat. No statistical main effects existed (p>0.050).

The maximum GRFv %SI showed good repeatability during each of the phases across the early, middle and entire repetition ranges with Cronbach's alpha values >= 0.901 (Table 4.3). However, there was not good maximum GRFv %SI repeatability during the late repetition range in the whole movement with Cronbach's alpha =0.679. The normalized net maximum GRFv showed poor repeatability with Cronbach's alpha values <=0.432 other than the late repetitions of the down phase which had good repeatability with a Cronbach's alpha = 0.704 (Table 4.4).

Table 4.3: Repeatability Assessment of Maximum GRFv %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.929	0.954	0.679	0.960
Down Phase	0.930	0.963	0.986	0.967
Up Phase	0.932	0.901	0.678	0.963

Table 4.4: Repeatability Assessment of Normalized Net Maximum GRFv: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	-0.114	-1.017	0.306	-0.355
Down Phase	0.432	-0.231	0.704	0.395
Up Phase	-0.086	-0.963	0.151	-0.388

38

Minimum GRFv

During the whole movement 5 of the 14 subjects had a larger minimum instantaneous value on their non-dominant limb over the 20 rep set. Additionally, only 4 subjects switched sides of force dominance from one rep range to another (Figure 4.12). Using the 10% asymmetry as the threshold for increased injury risk, 3 subjects crossed the 10% asymmetry threshold after the initial reps, however 3 others dropped from above to below the threshold over the whole movement (Figure 4.12). During the down phase, 5 of the 14 subjects had a larger minimum instantaneous value on their non-dominant limb over the 20 rep set. Additionally, only 1 subject switched sides of force dominance from one rep range to another (Figure 4.13). During the down phase, 2 subjects crossed the 10% asymmetry threshold after the initial reps, however one subject dropped from above to below the threshold during the middle reps and returned back above the 10% threshold (Figure 4.13). During the up phase, 7 of the 14 subjects had a larger minimum instantaneous value their non-dominant limb over the 20 rep set. Additionally, only 3 subjects switched sides of force dominance from one rep range to another (Figure 4.14). Four subjects crossed the 10% asymmetry threshold after the initial reps, however 1 subject dropped from above to below the threshold during the up phase (Figure 4.14). There were no statistically significant differences in the minimum GRFv |%SI| (Figure 4.15) during the whole movement, down phase or up phase over the each of the squat repetition ranges ($p >= 0.100$). However, there was a significant difference in the minimum GRFv %SI during the down phase, however, the Bonferroni post hocs only suggested approaching significance in the increase between the early and late reps (Figure 4.16). No statistically significant differences occurred in the normalized minimum net GRFv during the down phase or whole movement ($p>=0.193$). Additionally, increases occurred in the minimum net GRFv during the up phase ($p=0.005$),

39

although the Bonferroni post hocs only suggested approaching significance between the late and entire repetition ranges (p=0.093) (Figure 4.17).
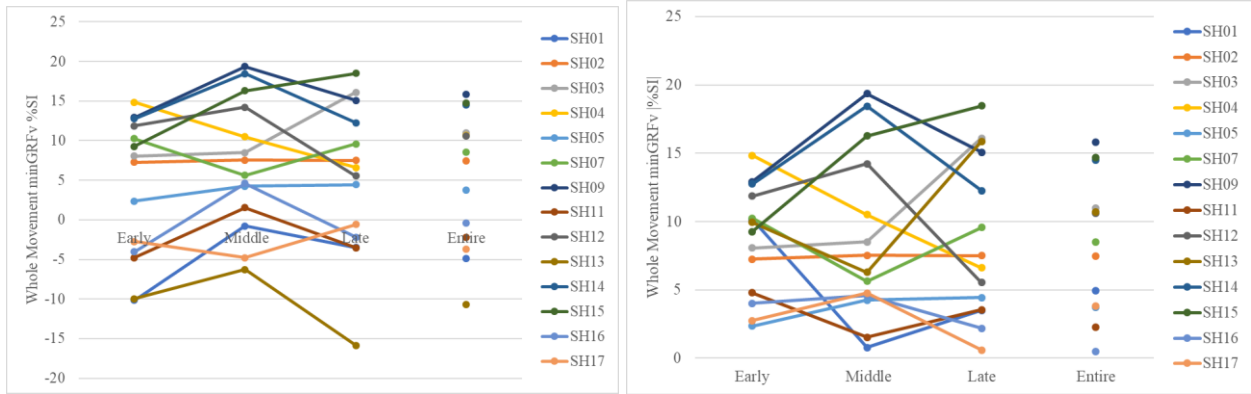

Figure 4.12: Individual minimum GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the whole movement.
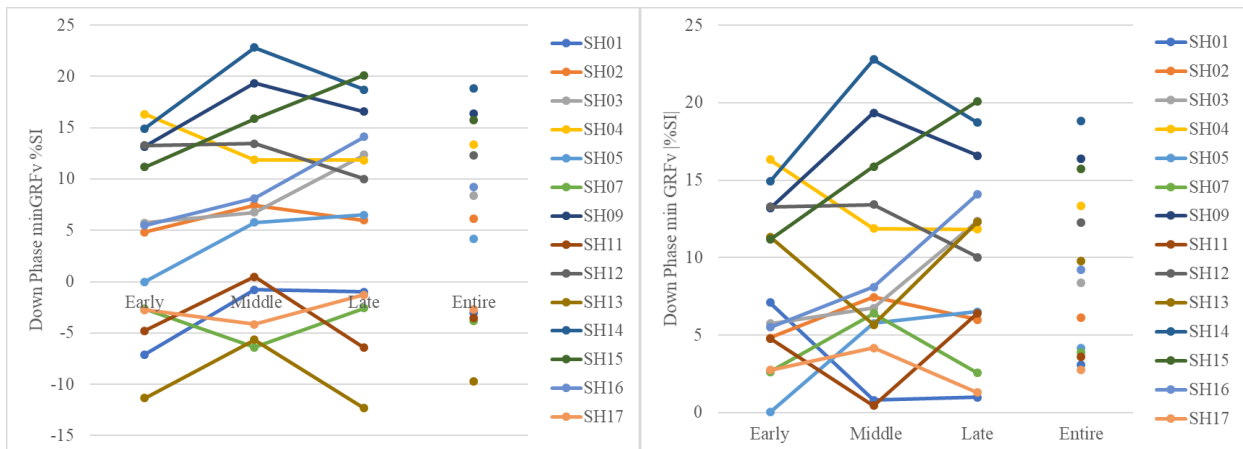

Figure 4.13: Individual minimum GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
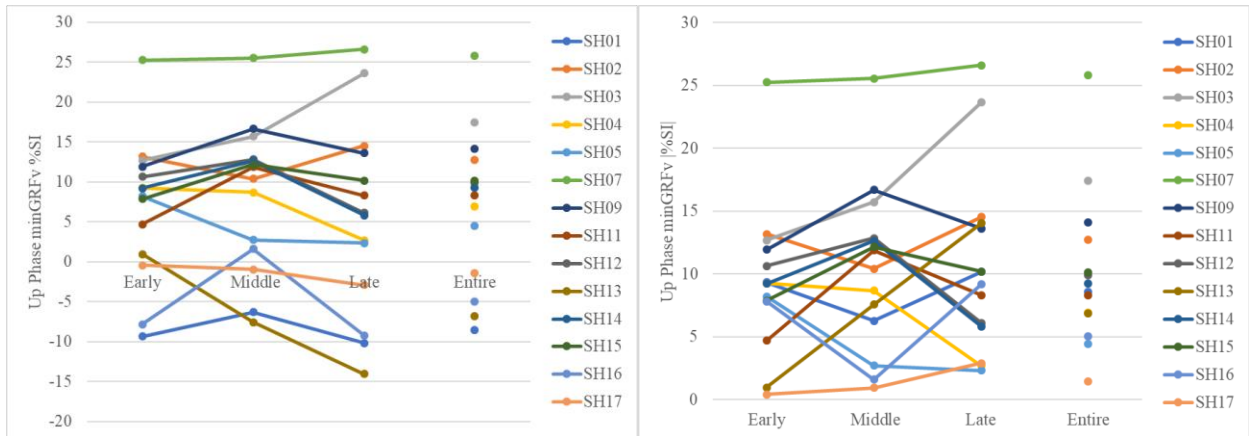
Figure 4.14: Individual minimum GRFv %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the up phase.
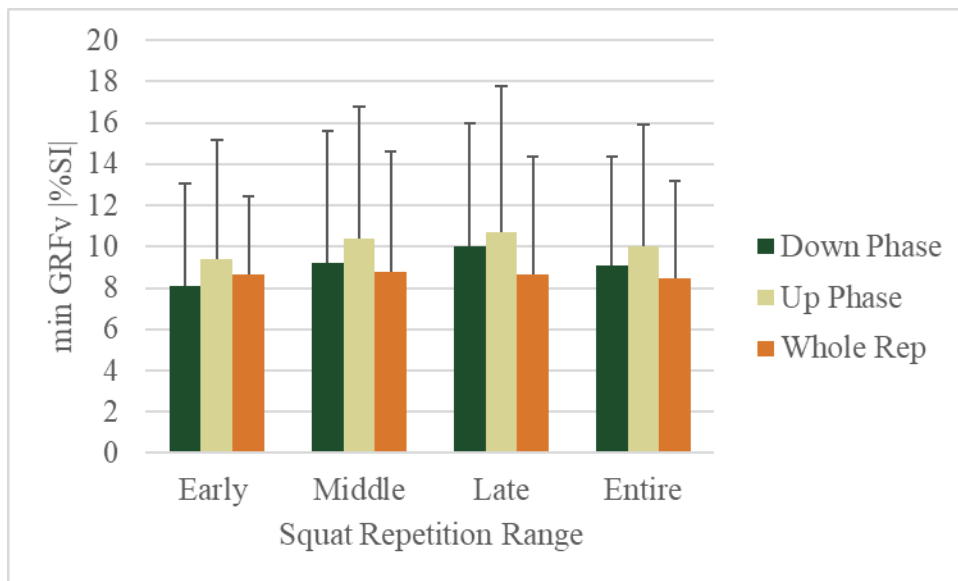

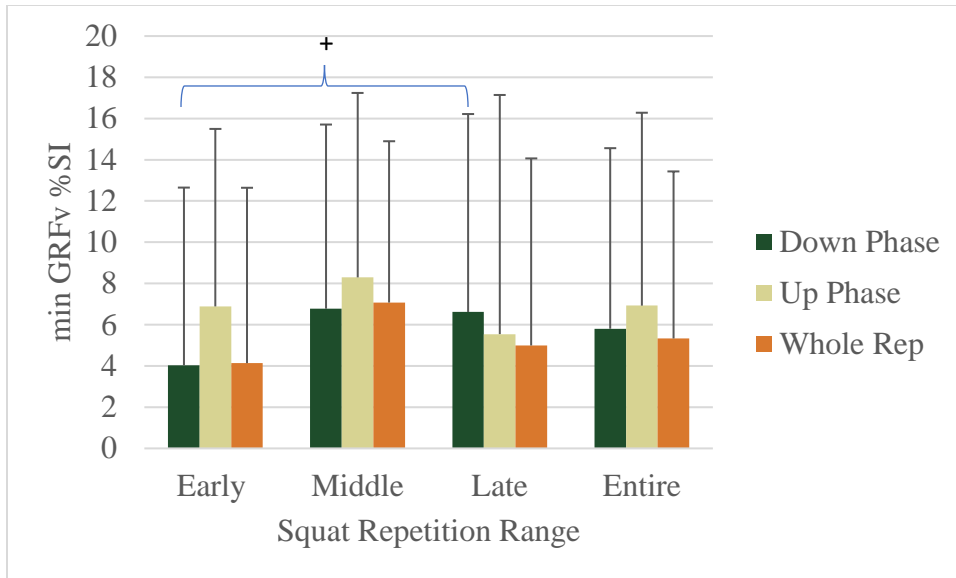Figure 4.15: Mean (+ 1 SD) minimum GRFv |%SI| during the BWT squat. No statistical main effects existed ($p > 0.050$).

Figure 4.15: Mean (+ 1 SD) minimum GRFv %SI during the BWT squat. + Indicates approaching statistical significance (0.050<p<0.100).
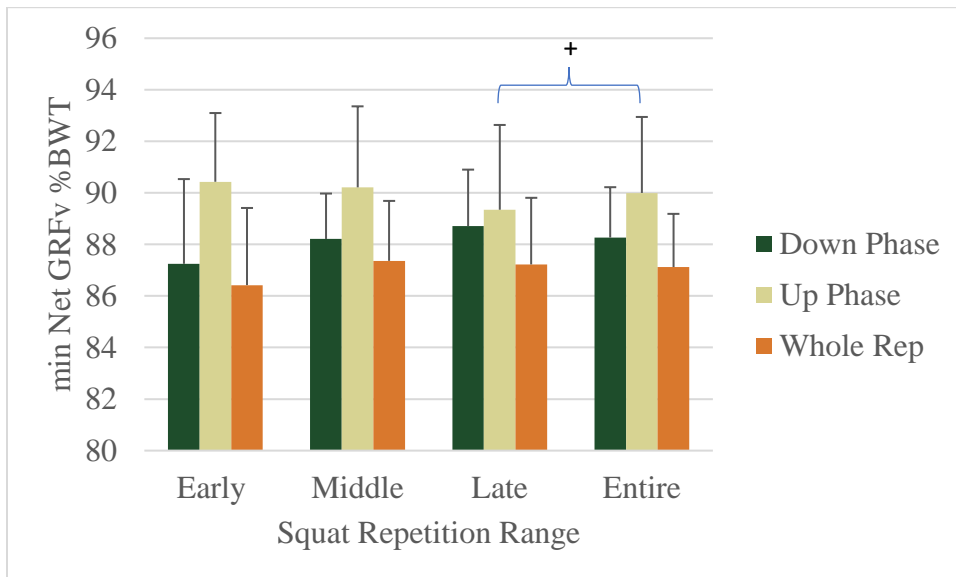

Figure 4.16: Mean (+ 1 SD) minimum net GRFv %BWT during the BWT squat. + Indicates approaching statistical significance (0.050<p<0.100).

The minimum GRFv %SI showed good repeatability during each of the phases across the early, middle and entire repetition ranges with Cronbach's alpha values $>= 0.702$ (Table 4.5). Furthermore, the net normalized minimum GRFv had good repeatability during the early whole movement and down phase with both having a Cronbach's alpha value of 0.838, although not all

phases and repetition ranges and had good repeatability considering most Cronbach's alpha

values <= were less than 0.666 (Table 4.6).

Table 4.5: Repeatability Assessment of Minimum GRFv %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.849	0.844	0.852	0.900
Down Phase	0.901	0.903	0.905	0.968
Up Phase	0.702	0.770	0.825	0.804

Table 4.6: Repeatability Assessment of Normalized Net Minimum GRFv: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.838	0.192	0.633	0.538
Down Phase	0.838	0.297	0.666	0.561
Up Phase	0.286	-0.342	0.372	0.168

ML Sway

During the whole movement 5 of the 14 subjects had larger sway on their non-dominant

limb over the 20 rep set. Additionally, only 4 subjects switched sides of sway dominance from

one rep range to another (Figure 4.17). Using the 10% asymmetry as the threshold for increased

injury risk, 4 subjects crossed the 10% asymmetry threshold after the initial reps, however 2

others dropped from above to below the threshold over the whole movement (Figure 4.17).

During the down phase, 5 of the 14 subjects had larger sway values on their non-dominant limb

over the 20 rep set. Additionally, only 4 subjects switched sides of sway dominance from one

rep range to another (Figure 4.18). During the down phase, 1 subject crossed the 10%

asymmetry threshold after the initial reps, however 1 subject dropped from above to below the

threshold during the ensuing reps (Figure 4.18). During the up phase 5 of the 14 subjects had

larger sway values on their non-dominant limb over the 20 rep set. Additionally, only 3 subjects

switched sides of sway dominance from one rep range to another (Figure 4.19).Three subjects

crossed the 10% asymmetry threshold after the initial reps, however 1 subject dropped from

above to below the threshold and returned back above the 10% threshold during the late reps of

the up phase (Figure 4.19). There were no statistically significant differences in the ML sway %SI (Figure 4.20) and |%SI| (Figure 4.21) across the rep ranges during the whole movement, up or down phases ($p>=0.322$). Additionally there were no statistically significant differences in normalized net sway (Figure 4.22) across the rep ranges during the whole movement, up or down phases ($p>=0.133$).
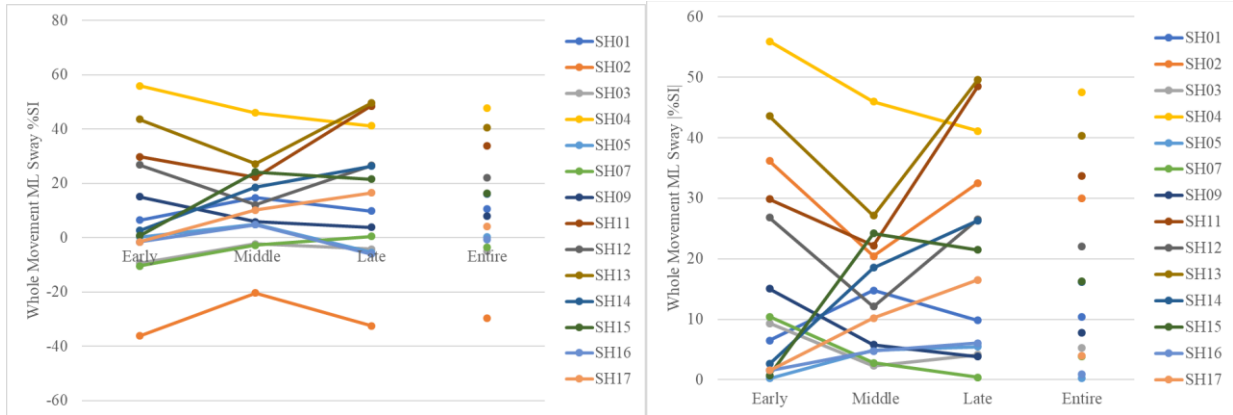

Figure 4.17: Individual ML Sway %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the whole movement.
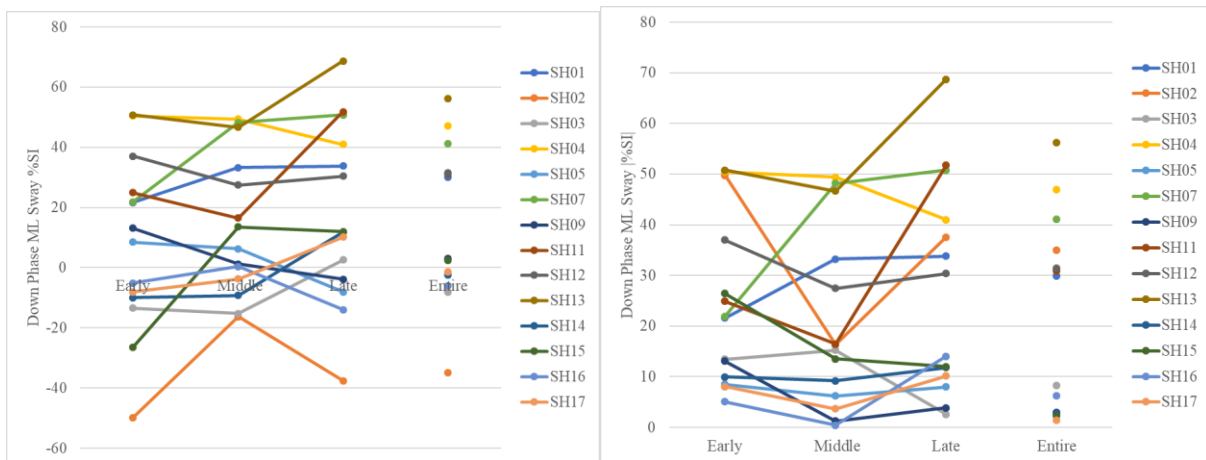

Figure 4.18: Individual ML Sway %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
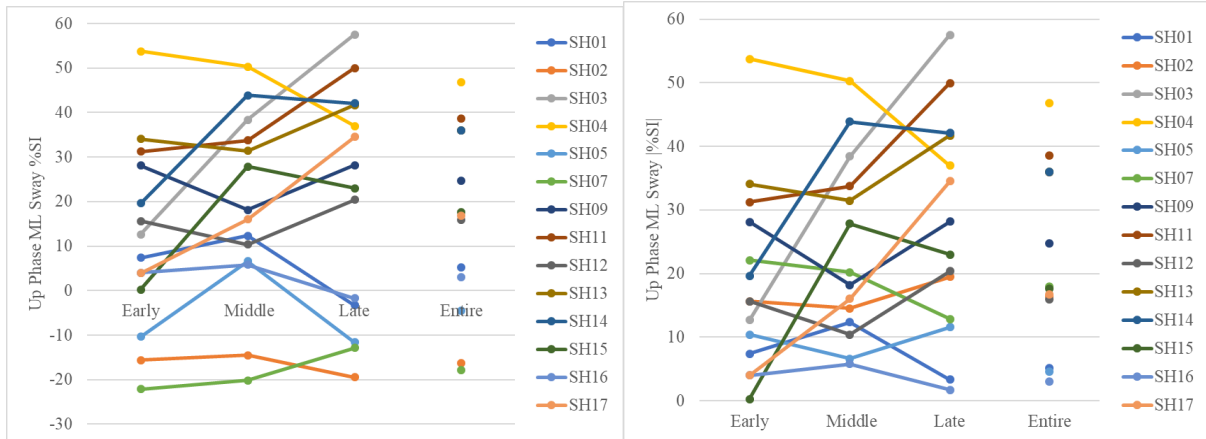
Figure 4.19: Individual ML Sway %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
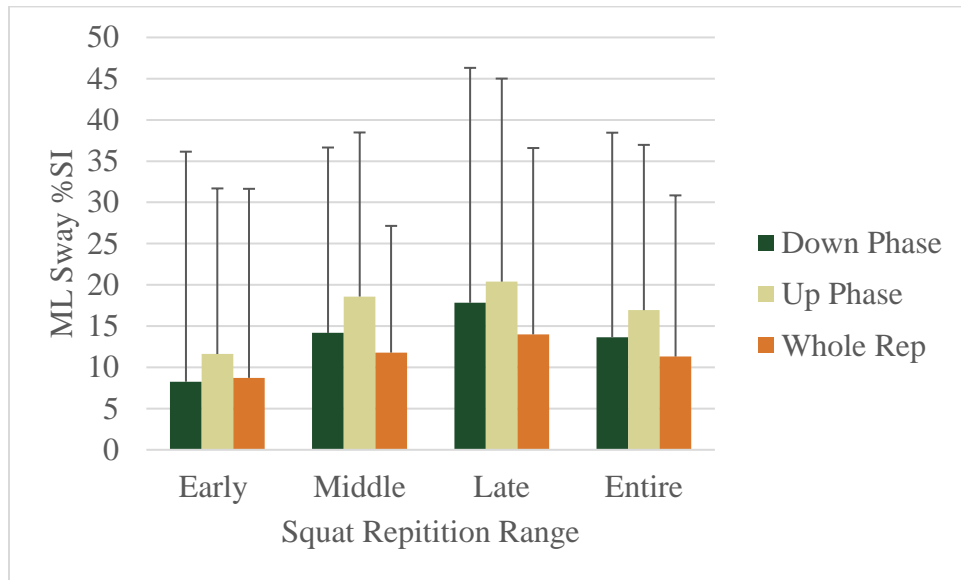
Figure 4.20: Mean (+ 1 SD) ML Sway %SI during the BWT squat. No statistical main effects existed (p>0.050).
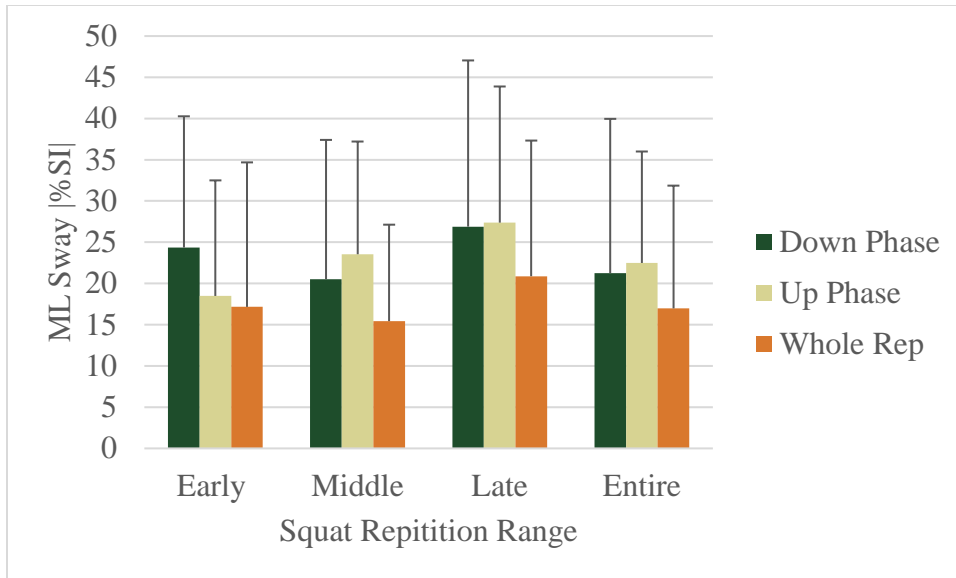
Figure 4.21: Mean (+ 1 SD) ML Sway |%SI| during the BWT squat. No statistical main effects existed (p>0.050).
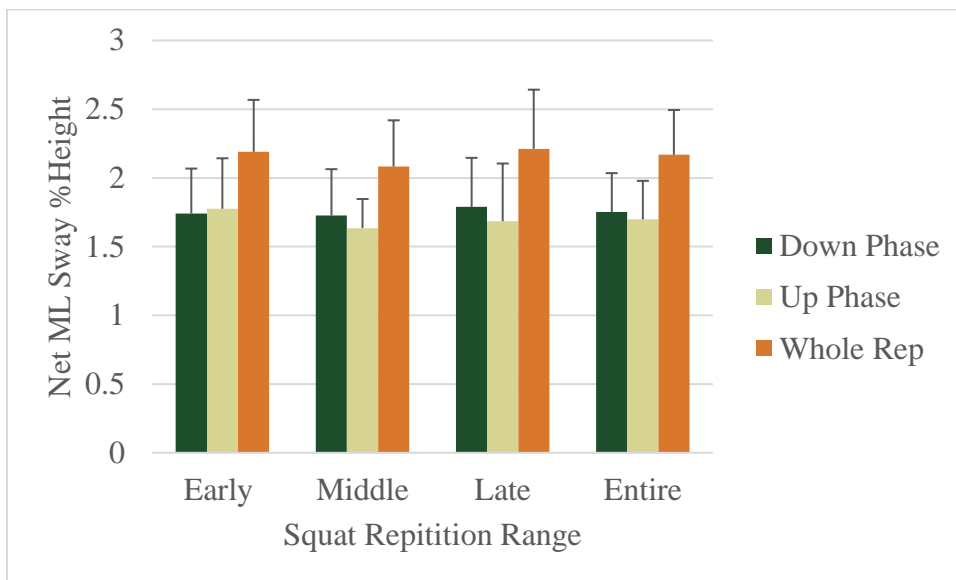
Figure 4.22: Mean (+ 1 SD) Net ML Sway %Height during the BWT squat. No statistical main effects existed (p>0.050).

The ML Sway %SI showed good repeatability during each of the phases across the early, middle, late, and entire repetition ranges with Cronbach's alpha values >= 0.802 (Table 4.7). The net normalized ML Sway had good repeatability during the early, middle and entire repetition ranges of the whole movement with Cronbach's alpha values >= 0.730 and during the

down phase of the middle, late and entire repetition ranges with Cronbach's alpha values

>=0.891, although the up phase had poor Cronbach's alpha values <=0.625 (Table 4.8).

Table 4.7: Repeatability Assessment of ML Sway %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.906	0.802	0.899	0.908
Down Phase	0.906	0.845	0.868	0.934
Up Phase	0.854	0.818	0.897	0.880

Table 4.8: Repeatability Assessment of Normalized Net ML Sway: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.730	0.784	0.684	0.846
Down Phase	0.615	0.968	0.914	0.891
Up Phase	0.572	0.426	-0.835	0.625

AP Sway

During the whole movement 8 of the 14 subjects had larger sway on their non-dominant

limb over the 20 rep set. Additionally, only 3 subjects switched sides of sway dominance from

one rep range to another (Figure 4.23). Using the 10% asymmetry as the threshold for increased

injury risk, 3 subjects crossed the 10% asymmetry threshold after the initial reps, however 3

others dropped from above to below the threshold during the middle reps and then returned

above the 10% asymmetry threshold during the late reps over the whole movement (Figure 4.23).

During the down phase 8 of the 14 subjects had larger sway on their non-dominant limb over the

20 rep set. Additionally, 5 subjects switched sides of sway dominance from one rep range to

another (Figure 4.24). During the down phase, 3 subjects crossed the 10% asymmetry threshold

after the initial reps, however 2 subjects dropped from above to below the threshold during the

ensuing reps and one of those subjects returned back to above the 10% asymmetry threshold

during the late reps (Figure 4.24). During the up phase 9 of the 14 subjects had larger sway on

their non-dominant limb over the 20 rep set. Additionally, 4 subjects switched sides of sway

dominance from one rep range to another (Figure 4.25). Two subjects crossed the 10%

asymmetry threshold after the initial reps, however 1 subject dropped from above to below the threshold during the up phase (Figure 4.25). Statistical increases in the AP sway %SI occurred during the early and late and late and entire ranges of the whole movement (p=0.006). Additionally, changes occurred during the AP sway %SI (p=0.006) during the down phase although, the Bonferroni post hocs only suggested approaching significance in an increase between the early and late and a decrease between late and entire reps (Figure 4.26). There were no significant changes in AP sway |%SI| (Figure 4.27) across the rep ranges during all phases of the movement (p>=0.243). There were also no changes in the AP sway %SI during the up phase (p>=0.064). There are no statistically significant changes in normalized net AP sway values (Figure 4.28) during the whole movement, down phase or, or phase across all repetition ranges (p>= 0.239).
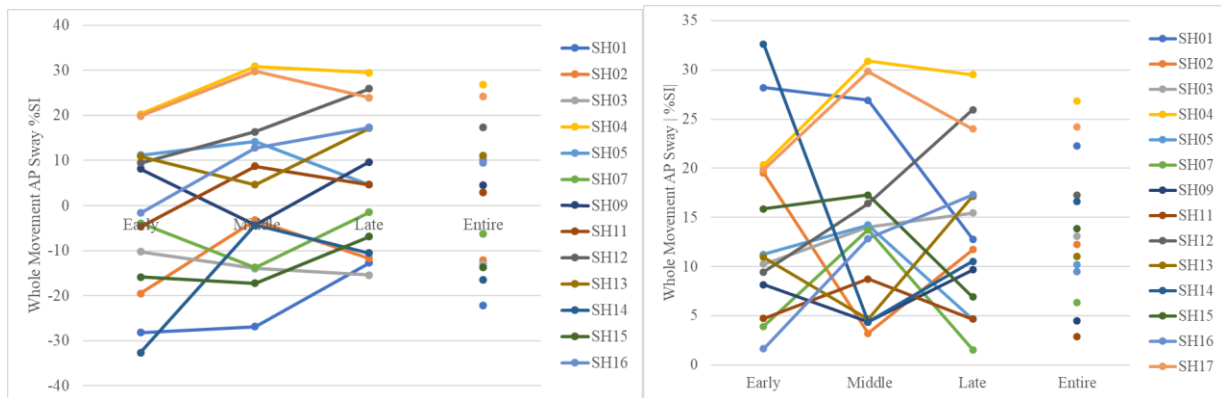
Figure 4.23: Individual AP Sway %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the whole movement.
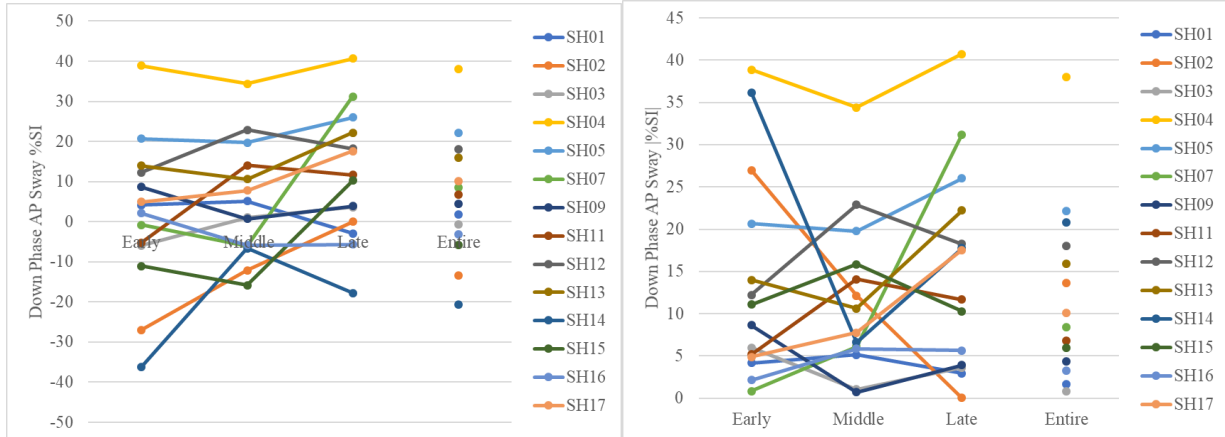
Figure 4.24: Individual AP Sway %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
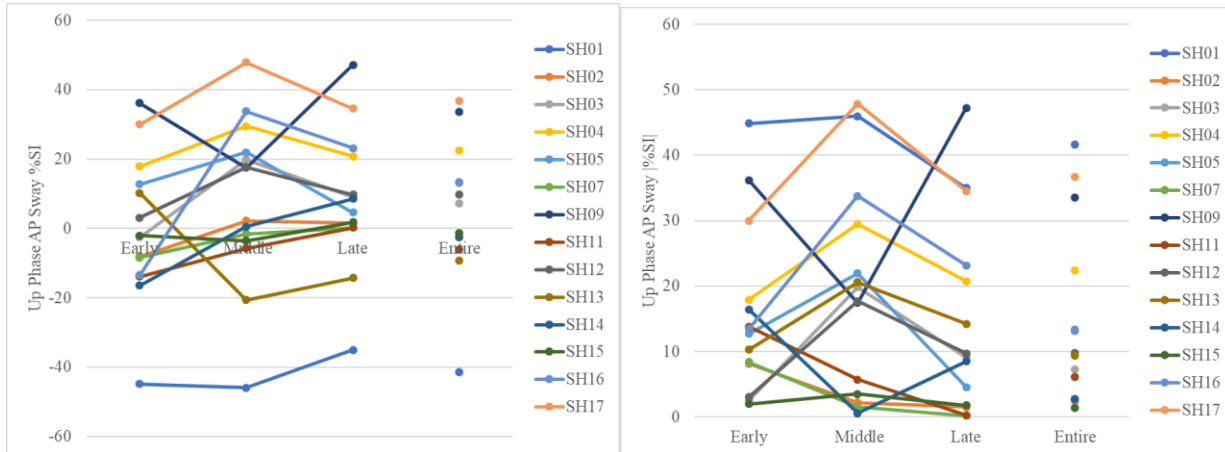
Figure 4.25: Individual AP Sway %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the up phase.
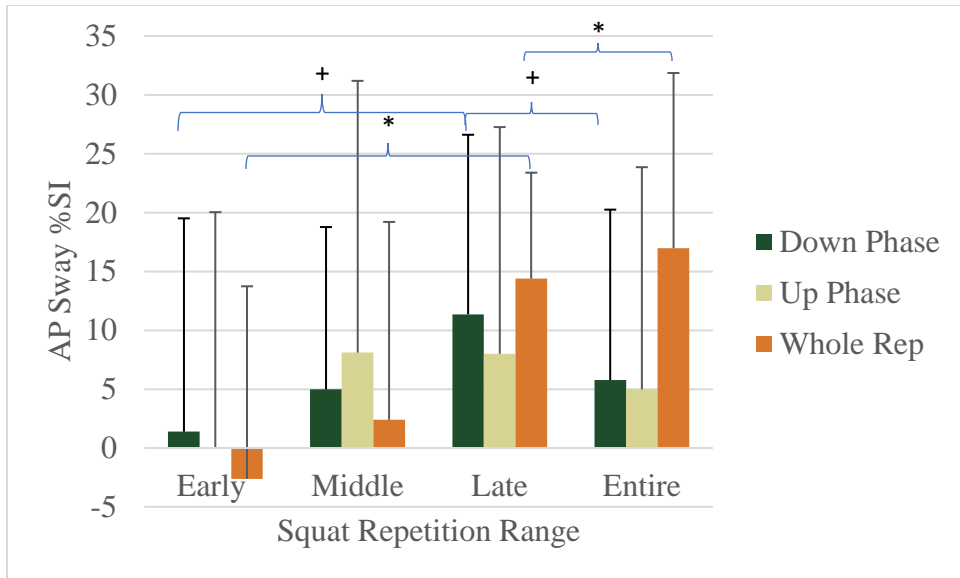
Figure 4.26: Mean (+ 1 SD) AP Sway %SI during the BWT squat. * Indicates a statistically significant difference (p<0.050), + indicates approaching statistical significance (0.050<p<0.100).
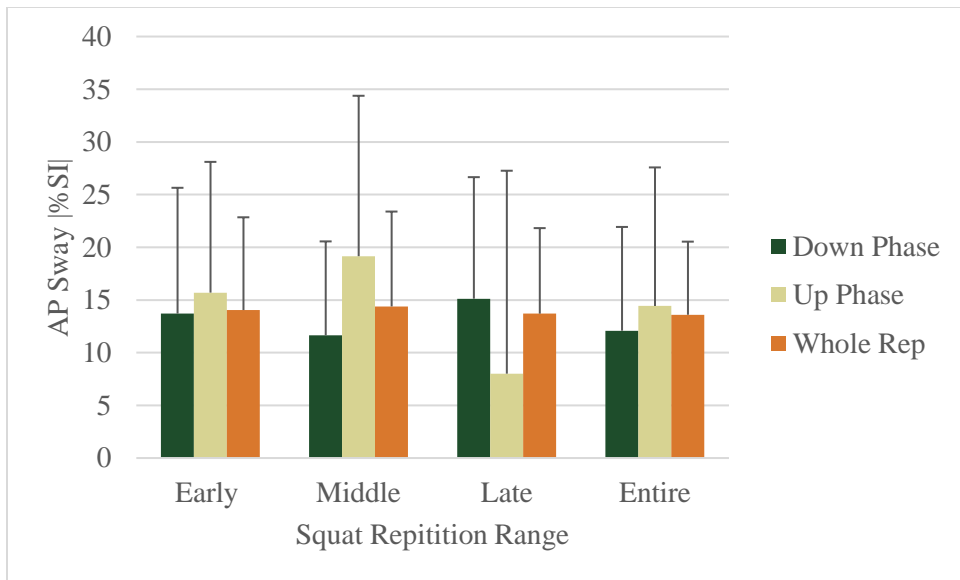
Figure 4.27: Mean (+ 1 SD) AP Sway |%SI| during the BWT squat. No statistical main effects existed (p>0.050).
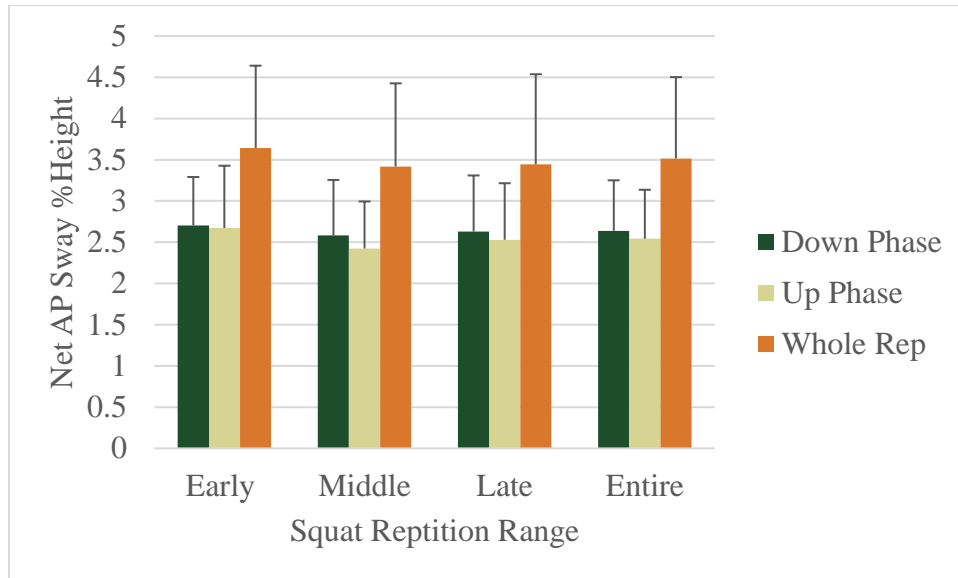
Figure 4.28: Mean (+ 1 SD) Net AP Sway %Height during the BWT squat. No statistical main effects existed (p>0.050).

The AP sway %SI showed good repeatability during the whole movement across each of the early, middle, late, and entire repetition ranges with Cronbach's alpha values >= 0.807. However, during the down phase, the AP sway %SI did not show good repeatability during the early and middle reps with Cronbach's alpha values <=0.645, although good repeatability was shown during the late and entire reps of the down phase with Cronbach's alpha values >=0.794. Furthermore, the up phase showed good repeatability with Cronbach's alpha values >=0.825. (Table 4.9). Additionally, the normalized net AP sway variables showed good repeatability during the early, middle (during down phase only) and entire reps of the whole movement and down phase with Cronbach's alpha values >=0.748. The normalized net AP sway variables showed poor repeatability during the up phase with Cronbach's alpha values <=0.361, except during the late reps which had a Cronbach's alpha value of 0.796 (Table 4.10).

Table 4.9: Repeatability Assessment of AP Sway %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.886	0.894	0.807	0.940
Down Phase	0.645	0.535	0.794	0.811
Up Phase	0.900	0.825	0.871	0.929

Table 4.10: Repeatability Assessment of Normalized Net AP Sway: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.817	0.476	0.503	0.778
Down Phase	0.823	0.836	0.365	0.748
Up Phase	0.361	-1.309	0.796	0.333

ML Path Length

During the whole movement only 3 of the 14 subjects had a larger path length on their non-dominant limb over the 20 rep set. Additionally, only 2 subjects switched sides of path length dominance from one rep range to another (Figure 4.29). Using the 10% asymmetry as the threshold for increased injury risk, 1 subject crossed the 10% asymmetry threshold after the initial reps, however 4 others dropped from above to below the threshold during the middle reps and then 2 returned above the 10% asymmetry threshold during the late reps over the whole movement (Figure 4.29). During the down phase only 3 of the 14 subjects had a larger path length on their non-dominant limb over the 20 rep set. Additionally, only 2 subjects switched sides of path length dominance from one rep range to another (Figure 4.30). During the down phase, 2 subjects crossed the 10% asymmetry threshold after the initial reps, however 4 subjects dropped from above to below the threshold during the ensuing reps and 2 of those subjects returned back to above the 10% asymmetry threshold during the late reps (Figure 4.30). During the up phase only 1 of the 14 subjects had a larger path length on their non-dominant limb over the 20 rep set (Figure 4.31). One subject crossed the 10% asymmetry threshold after the initial reps, however 3 subjects dropped from above to below the threshold and two of these subjects returned above the asymmetry threshold during the up phase (Figure 4.31). No statistically

significant differences occurred in the ML path length %SI (Figure 32) and |%SI| (Figure 33) during the whole movement, down phase and up phase across and repetition ranges (p>=0.180). Additionally, there are no statistically significant changes in net ML path length (Figure 34) during the whole movement, down phase and up phase over each of the squat repetition ranges (p>= 0.580).
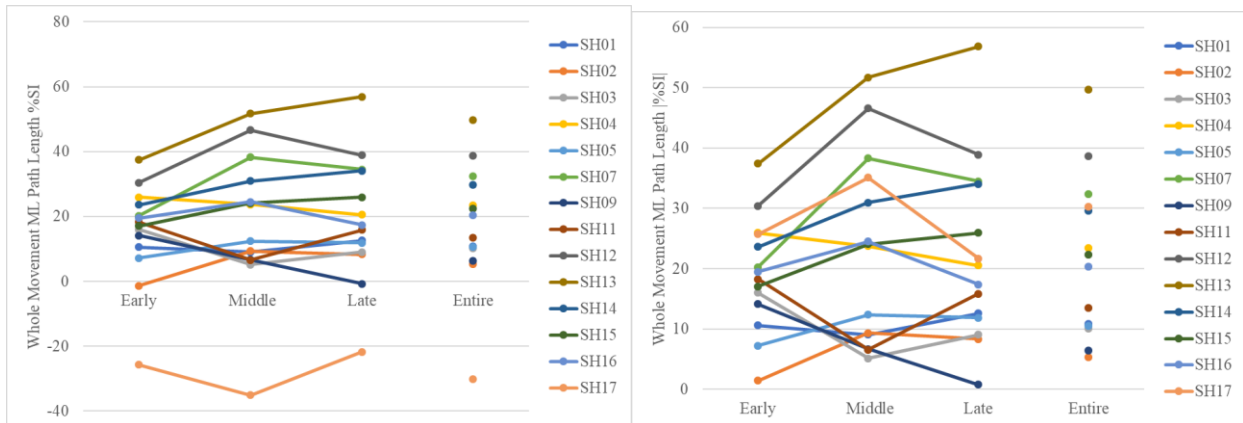
Figure 4.29: Individual ML Path Length %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the whole movement.
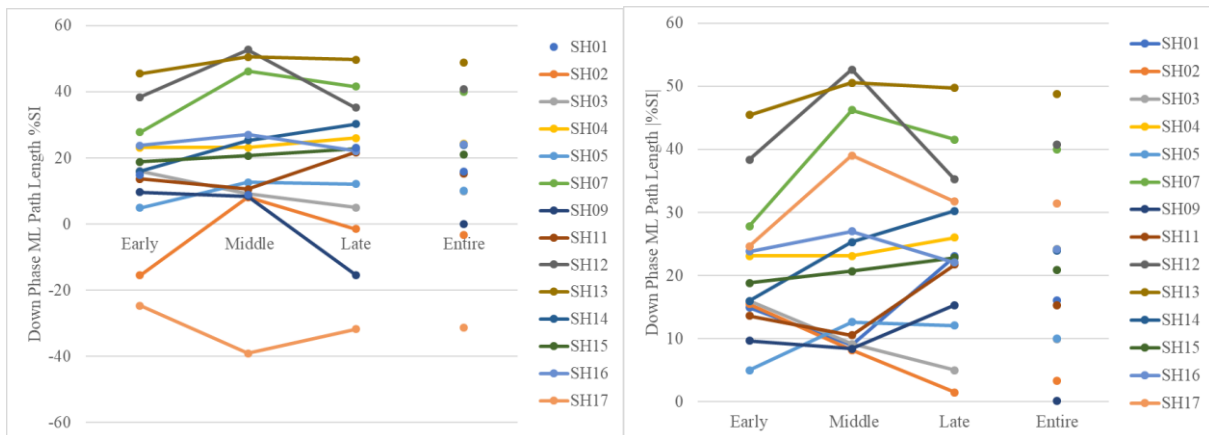
Figure 4.30: Individual ML Path Length %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
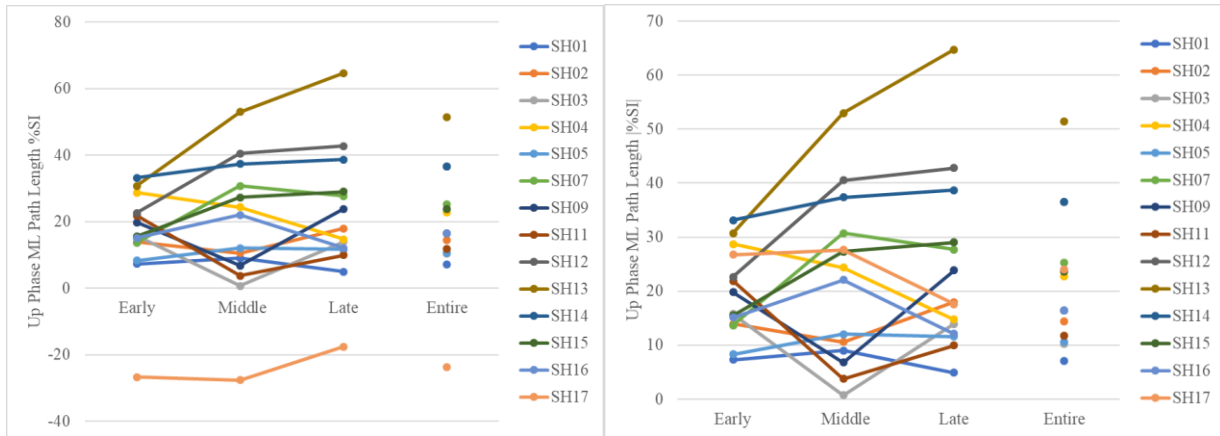
Figure 4.31: Individual ML Path Length %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the up phase.
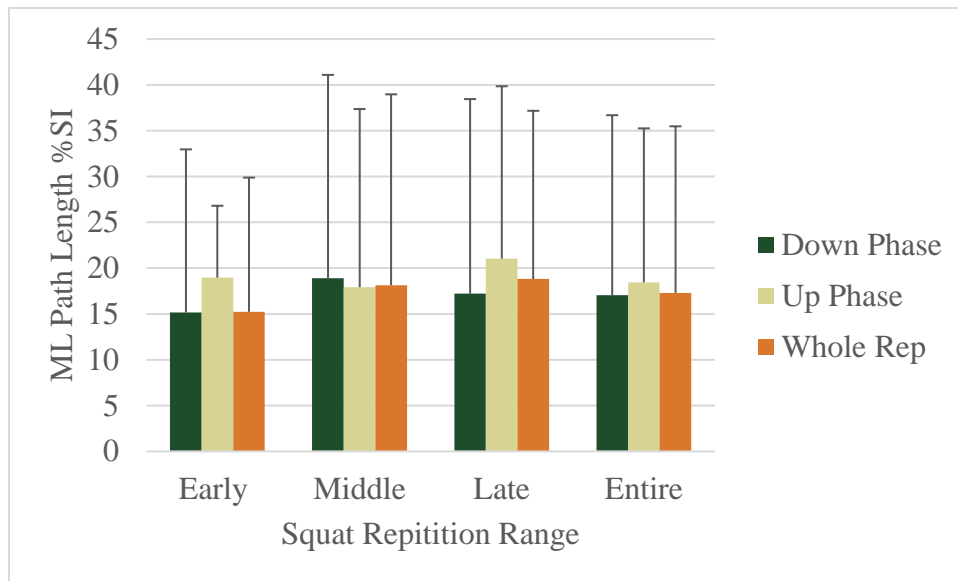
Figure 4.32: Mean (+ 1 SD) ML Path Length %SI during the BWT squat. No statistical main effects existed (p>0.050).
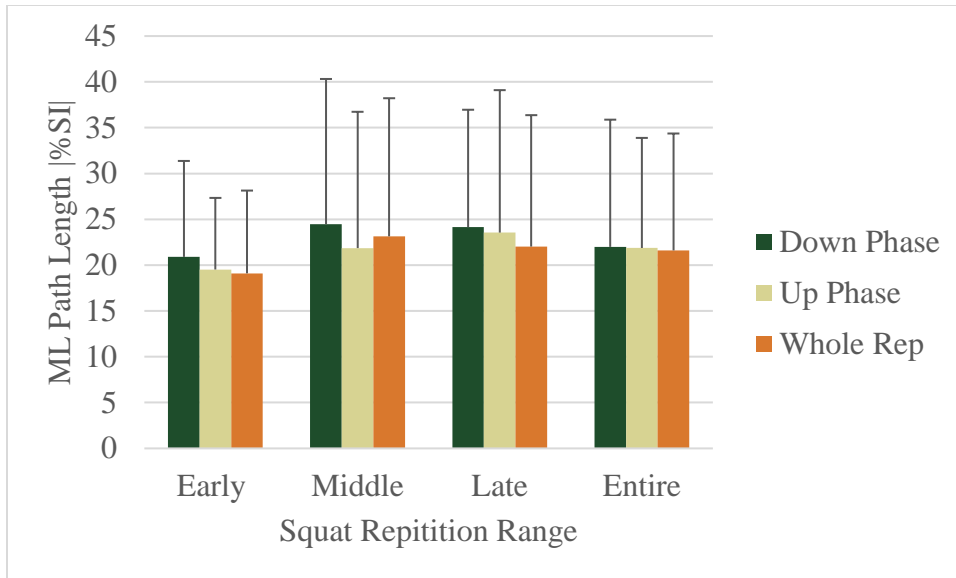
Figure 4.33: Mean (+ 1 SD) ML Path Length |%SI| during the BWT squat. No statistical main effects existed (p>0.050).
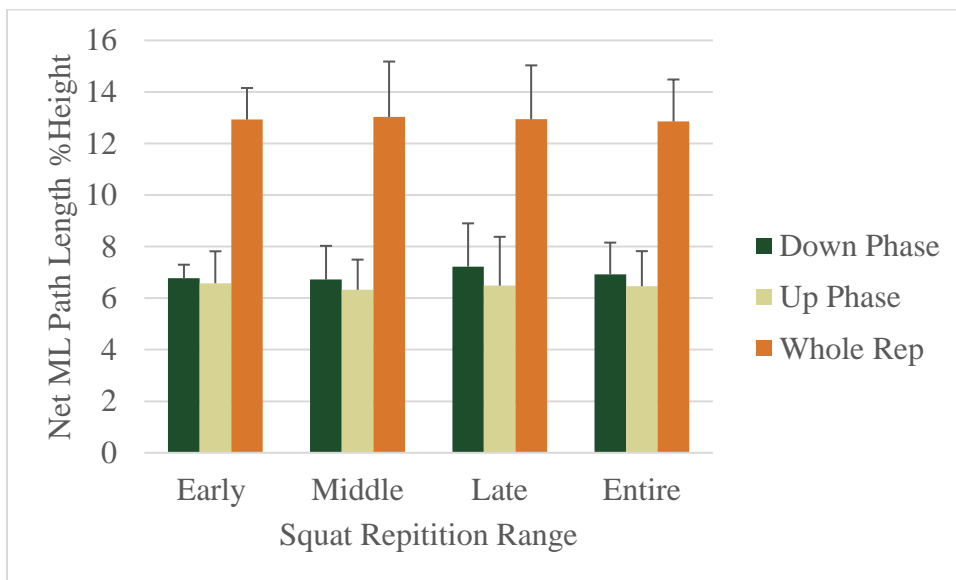
Figure 4.34: Mean (+ 1 SD) Net ML Path Length %Height during the BWT squat. No statistical main effects existed (p>0.050).

The ML path length %SI showed good repeatability during the whole movement, down phase and up phase across each of the early, middle, late, and entire repetition ranges with Cronbach's alpha values >= 0.890 except for the early up phase which has a Cronbach's alpha value of 0.699 (Table 4.11). Additionally, the normalized net ML path length showed good

repeatability for each of the variables other than the early whole movement which had a Cronbach's alpha value of 0.687 (Table 4.12). The additional normalized net ML path lengths had Cronbach's alpha values >= 0.755.

Table 4.11: Repeatability Assessment of ML Path Length %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.931	0.984	0.890	0.987
Down Phase	0.913	0.971	0.943	0.981
Up Phase	0.699	0.909	0.977	0.989

Table 4.12: Repeatability Assessment of Normalized Net ML Path Length: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.687	0.905	0.985	0.977
Down Phase	0.852	0.962	0.952	0.959
Up Phase	0.934	0.755	0.958	0.965

AP Path Length

During the whole movement 5 of the 14 subjects had a larger path length on their non-dominant limb over the 20 rep set. Additionally, only 3 subjects switched sides of path length dominance from one rep range to another (Figure 4.35). Using the 10% asymmetry as the threshold for increased injury risk, 5 subjects crossed the 10% asymmetry threshold after the initial reps, however 2 others dropped from above to below the threshold over the whole movement (Figure 4.35). During the down phase only 3 of the 14 subjects had a larger path length on their non-dominant limb over the 20 rep set. Additionally, only 1 subject switched sides of path length dominance from one rep range to another (Figure 4.36). During the down phase, 6 subjects crossed the 10% asymmetry threshold after the initial reps, however 2 subjects dropped from above to below the threshold during the ensuing reps (Figure 4.36). During the up phase 6 of the 14 subjects had a larger path length on their non-dominant limb over the 20 rep set. Additionally, 5 subjects switched sides of path length dominance from one rep range to another (Figure 4.37). Four subjects crossed the 10% asymmetry threshold after the initial reps,

however 2 subjects dropped from above to below the threshold and both of the subjects returned above the asymmetry threshold during the up phase (Figure 4.37). There were significant differences in the AP path length %SI during the whole movement although the Bonferroni post hocs only suggested approaching significance with an increase between the early and late and a decrease between the late and entire rep ranges (Figure 4.38). Additionally, there is a significant increase between the AP path length %SI during the early and entire and early and middle rep ranges of the down phase. No statistical differences occurred between the AP path length |%SI| (Figure 4.39) across all rep ranges and phases (p>=0.070). Furthermore, there was a statistically significant change during the down phase of the net AP path length, although the Bonferroni post hocs showed no statistically significant differences between the repetition ranges (p=0.031). There were no statistical differences between the normalized net AP path length (Figure 4.40) over each of the repetition ranges during the whole movement or up phase (p>=0.124).
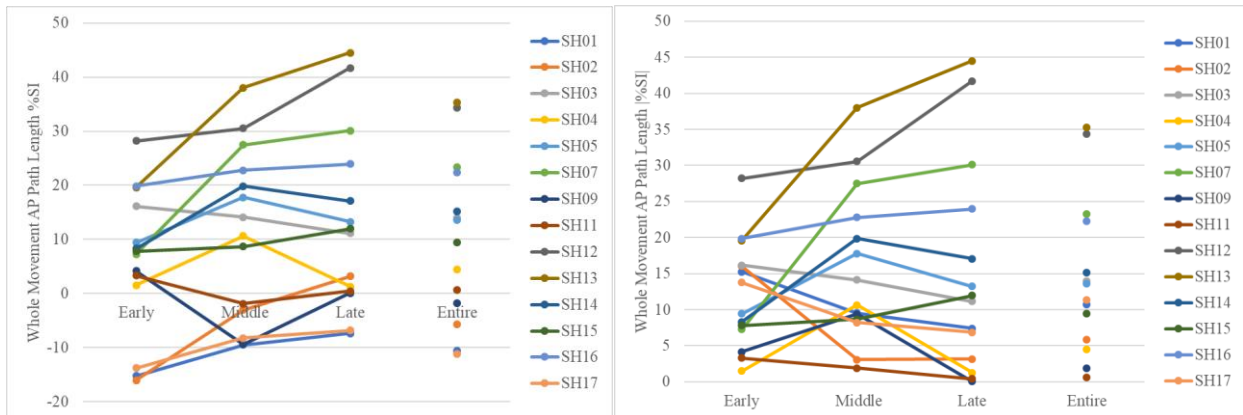
Figure 4.35: Individual AP Path Length %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the whole movement.
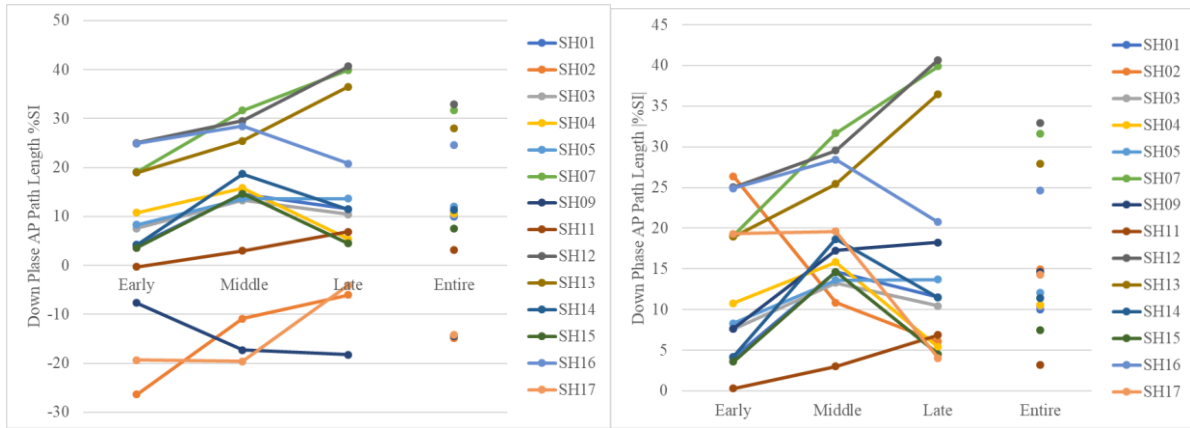
Figure 4.36: Individual AP Path Length %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the down phase.
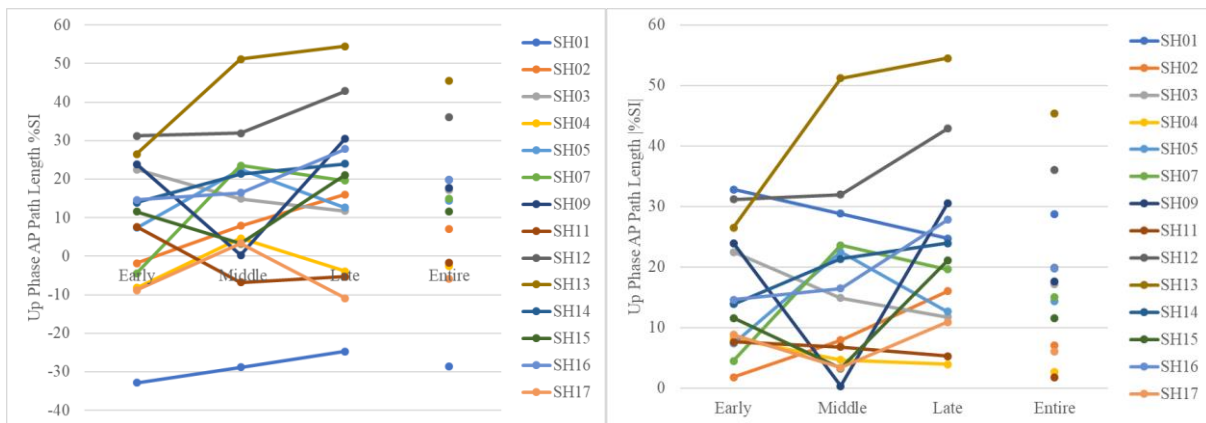
Figure 4.37: Individual AP Path Length %SI (left) and |%SI| (right) during early, middle, late and entire repetition ranges of the up phase.
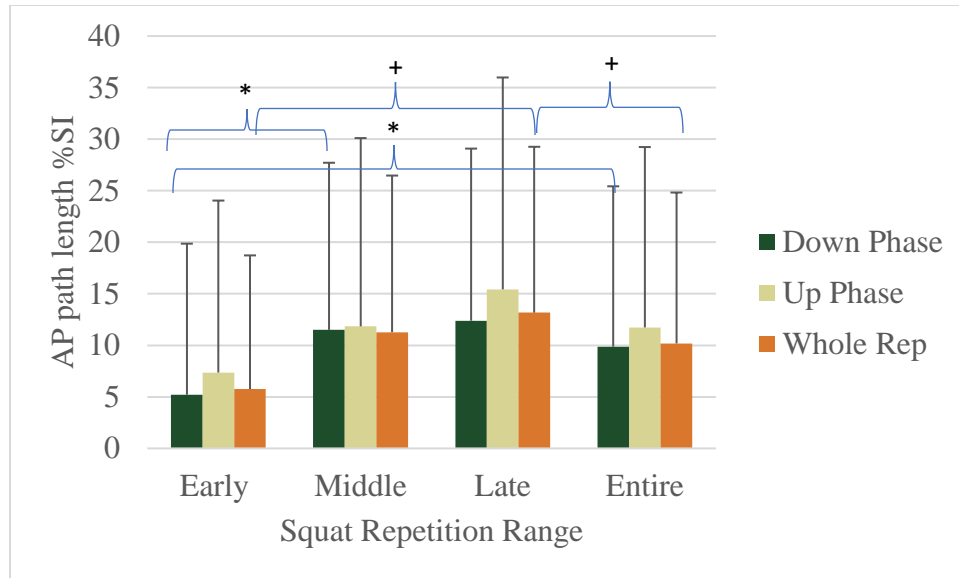
Figure 4.38: Mean (+ 1 SD) AP path length %SI during the BWT squat. * Indicates a statistically significant difference (p<0.050), + indicates approaching statistical significance (0.050<p<0.100).
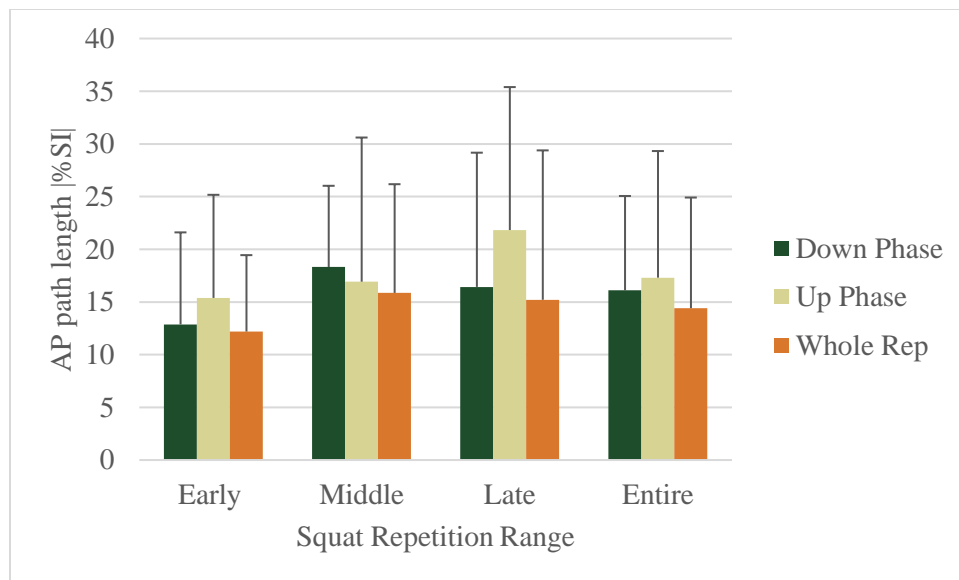
Figure 4.39: Mean (+ 1 SD) AP path length |%SI| during the BWT squat. No statistical main effects existed (p>0.050).
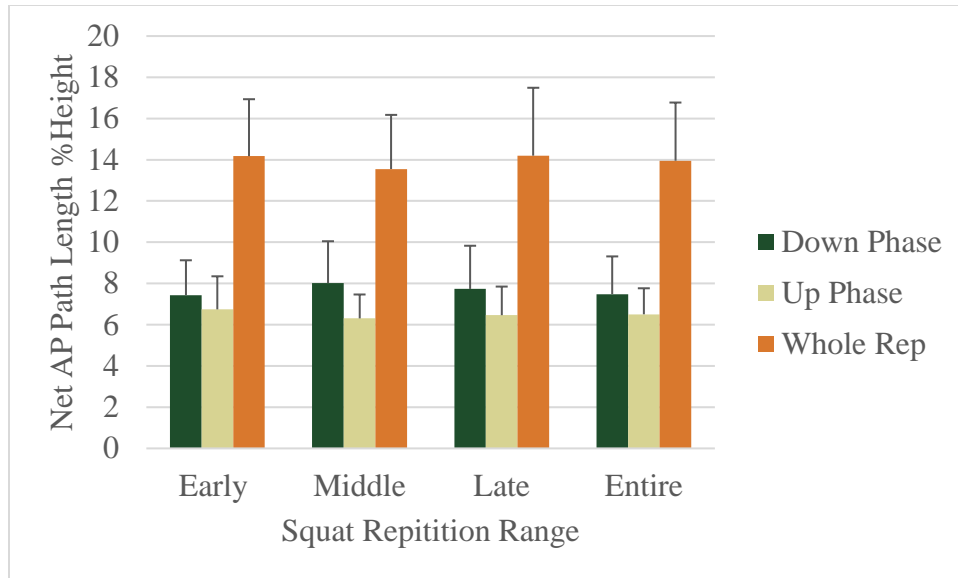
Figure 4.40: Mean (+ 1 SD) normalized net AP path length %Height during the BWT squat. No statistical main effects existed (p>0.050).

The AP path length %SI showed good repeatability during the whole movement, down phase and up phase across each of the early, middle, late, and entire repetition ranges with Cronbach's alpha values >= 0.756 (Table 4.13). Additionally, the normalized net AP path length showed good repeatability during the whole movement, down phase and up phase across each of the early, middle, late and entire repetition ranges with Cronbach's alpha values p>= 0.799 (Table 4.14).

Table 4.13: Repeatability Assessment of AP Path Length %SI: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.756	0.840	0.958	0.897
Down Phase	0.835	0.919	0.853	0.915
Up Phase	0.784	0.780	0.983	0.919

Table 4.14: Repeatability Assessment of Normalized Net AP Path Length: Chronbach's alpha

	Early	Middle	Late	Entire
Whole movement	0.945	0.981	0.960	0.969
Down Phase	0.973	0.987	0.957	0.984
Up Phase	0.799	0.949	0.933	0.916

CHAPTER V

DISCUSSION

The goal of this investigation was to analyze potential differences in force platform GRFv and CoP values over 20 repetitions of the bilateral BWT squat in recreationally competitive active women. It was hypothesized that on average, due to increases in some individuals, there would be changes in asymmetries and normalized values from the early repetition ranges to the later repetition ranges in the up phase, down phase, and the whole movement. Furthermore, we hypothesized that there would be evidence of fatigue in later repetitions of the 20 BWT squats and that the measures would be highly repeatable from day-to-day. The hypothesis was partially supported by the results in that both asymmetries and normalized values changed in some subjects over the repetition ranges, although not all measures analyzed produced group level changes from the early repetition ranges to the later repetition ranges. Furthermore, there was limited evidence supporting fatigue and many of the measures were highly repeatable.

Individual Subject Data

Individual subject data was assessed in order to determine if there were varying levels of asymmetry in the subjects, detect potential asymmetry patterns across subjects and identify subjects that did not adhere to potential asymmetry patterns. Furthermore, individual subject data was assessed to determine if subjects crossed the 10% asymmetry threshold after the first few reps, either increasing or decreasing their asymmetries. A cut off of |10%SI| was used as a high level of asymmetry as it was suggested by Hart et al. (2014) that above a 10% asymmetry, the risk for severe injury increases. Although, this threshold was determined with fresh athletes performing a limited number of reps. Therefore, further research will be necessary to determine

61

if this 10% cut off still holds in fatiguing/extended repetition protocols, or if a different threshold value should be used. It is also not clear if the 10% threshold is appropriate for all variables, or if some should be higher or possibly lower. As expected with this cut off, it was found that across all variables, there were subjects that were at high levels and low levels of asymmetry, with most subjects below the 10% threshold. Subjects showing different levels of asymmetry is supported by a study in elite youth soccer players showing varying levels of asymmetry among different athletes, even when 'healthy' (Read, 2016). The majority of subjects who were above the 10% cut off continued, or increased %SI, additionally the majority of subjects who were below the 10% cut off stayed below 10%SI across all repetition ranges. This contrasts with two previous studies that measured asymmetries during fatiguing squat protocols. Hodges et al. (2011) and Webster et al. (2015) both observed either no change in asymmetry with fatigue, or a reduction in asymmetry amongst those with higher levels. This could be due to the fact that the prior studies were much more fatiguing than ours. Interestingly, for each of the GRFv and postural sway variables, there were 3 to 4 subjects that had a |%SI| below 10% during the early squat repetition range, although their |%SI| increased to close to or above 10% during the middle or late squat repetition ranges. This shows that without performing 10 to 12 squats, some individuals would not be detected by the current 10% injury risk threshold. Furthermore, for each of the GRFv and postural sway variables, there were 1 to 2 subjects that had a |%SI| above 10% but then dropped below the 10% threshold during later reps, providing a possible false positive of asymmetry injury risk. This could explain the results of a study regarding injury prediction of the FMS is good at predicting injury (specificity score of 0.91 with 95% CI = 0.83-0.96) for those with a low score, but misses predicting too many people who were injured (sensitivity score of 0.54 with 95% CI = 0.34-0.68) (Kiesel, 2007). Moreover in the deep squat

test alone, similar results were found with being able to predict low scores with injury but many

who were scored high sustained an injury with odds ratio scores of 1.09 (95% CI = 0.35-3.39)

and 1.14 (95% CI = 0.39-3.32) for scores of 1 and 2 respectively (Warren, 2015). This is a very

important finding, because it shows that although the BWT squat is a good functional movement

assessment tool, the usual 3 to 5 squats are not enough to pick up asymmetries and change in

normalized values in a large enough group of people that are in fact at an increased risk for a

non-contact lower limb injury. Furthermore, by increasing the number of BWT squat reps from

3 to 5 to 10 to 12, more athletes who are at an increased risk for lower limb injury might be

detected and therefore, preventative measures can be taken to decrease their risk for injury.

Finally, these observations underscore the need to look at individuals along with group averages.

With some individuals increasing in value and others decreasing across the reps, the group

average will not change even though individual risk may be further explored.

Squat Phases

The down phase, up phase, and whole movement of the squat were analyzed in order to

determine weather changes in eccentric verses concentric movement contractions occurred over

repetition ranges. Although there were statistically significant increases that occurred during the

down phase for the same variable as the whole movement or up phase for the same variable as

the whole movement, there were not statistically significant changes in the down phase for the

same variable as the up phase. This shows that concentric and eccentric muscle contractions

elicited different asymmetry responses to increase in repetition ranges. This is supported by

Dionisio et al. (2008), who showed activation differences in muscles during the eccentric and

concentric phases of the BWT squat. They reported that both the gastrocnemius and tibialis

anterior were activated during the eccentric phase to provide ankle stabilization, while the

concentric phase had strong activation of the quadriceps in order to increase knee extensor joint torque (Dionisio et al., 2008). Furthermore, Leal de Souza (2017), who also collected EMG during the BWT squat, showed that the RMS amplitude of the rectus femoris was significantly greater during the eccentric phase than the concentric phase (p<0.001). Since different muscles are primarily activated and with different amplitudes during the two phases of the BWT squat, it is possible that primary muscles used for flexion and extension produce different GRFv and postural sway values and responses to additional reps. This would explain why the down phase and up phase do not show significantly significant variable differences during the same squat repetition ranges. Thus, it is important to measure both of the eccentric and concentric phases of the BWT squat.

Maximum GRFv, Minimum GRFv, ML Sway and Path Length %SI and Normalized Data

Maximum and minimum GRFv and ML sway and path length had limited statistically significant differences in asymmetries across the rep ranges. There has not been prior research conducted on maximum GRFv values of the BWT squat and there was no statistically significant differences in the %SI and |%SI| maximum GRFv variables during any of the phases of the BWT squat. Furthermore, there were no statistically significant differences in the minimum GRFv %SI values during each of the phases across the repetition ranges, although approaching significance in the minimum GRFv %SI values with an increase in minimum GRFv during the down phase from the early to the late squat repetition ranges. In addition to the maximum GRFv values during the BWT squat, there is no prior research investigating minimum GRFv during the BWT squat. A change in technique might provide a reason as to why maximum and minimum GRFv would have changed over the reps. Potentially, a reason why there wasn't a statistically significant change in the maximum and minimum GRFv values over the reps is due

to the use of our recording that acted as a metronome in order to standardize the timing of the squats. Without the use of the recording, there might be statistically significant changes in the maximum and minimum GRFv values due to subjects speeding up or slowing down their squats over the reps. ML sway and path length variables also did not show statistically significant changes across squat repetition ranges for both %SI and |%SI|. Although there are no previous studies that analyzed ML sway and path length during the BWT squat, a study investigating the effect of a fatiguing squat protocol on quiet stance postural sway velocity has been conducted. Similarly to our study, no significant differences were found between the quiet stance preliminary ML postural sway velocity results and the ML postural sway velocity results after the fatiguing squat protocol (Bission, 2011). Finally, no statistically significant differences occurred in the net normalized values over the squat repetition ranges for the variables other than the minimum GRFv and AP path length variables. Significance was approached in an increase in minimum net GRFv %BWT during the up phase between the late and entire squat repetition ranges. Furthermore, there is no prior research analyzing net normalized GRFv or postural sway variables. Since there were no statistically significant differences, it might not be useful to study these variables. Even though there were no statistically significant differences found in the maximum GRFv, minimum GRFv, ML sway and path length and net normalized data, individual subject data showed some individuals increased their asymmetries above the 10% threshold or decreased below the 10% threshold after the first few reps. Therefore, it might not be important to study maximum GRFv, minimum GRFv and ML sway and path length as a population average, but individually to determine potential injury risk.

Limb Dominance

The average GRFv %SI values showed no statistically significant differences over the squat repetition ranges, although the average GRFv |%SI| values did show statistically significant changes from the early to middle squat repetition ranges. This suggests that there were changes in average GRFv in subjects that favored their non-dominant leg in addition to subjects that favored their dominant leg, since the positive and negative values may have cancelled each other out during the relative averages. This was supported by a study analyzing kinematic asymmetry during walking tasks that showed that although lower extremity asymmetries existed in some subjects, these asymmetries could not be correlated with lower limb laterality (Gunderson, 1989 via Brown, 2014). Although, limb dominance was unaffected in average GRFv asymmetry values, it was found that subjects had increasing AP sway and path length %SI values over the squat repetition ranges showing that AP path length and sway increased towards their dominant limbs over the squat repetition ranges. Since AP sway and path length are similar metrics, it is expected that they would have comparable trends. Contrary to the average GRFv results, the AP sway and path length values were affected by limb dominance. These findings are supported by a study showing larger AP path length values in dominant legs during a kicking task where CoP data was analyzed on supporting legs, suggesting that there is a lower amount of sway and shorter path length on the non-dominant leg (King, 2017). Thus, as repetition increases during the BWT squat, control on the dominant limb increases compared to the non-dominant limb where it decreases.

Fatigue

The study aimed at measuring the changes of postural control and GRFv variables with fatigue during the BWT squat. Fatigue was to be assessed with the CoP measures. As

hypothesized it was found that the net AP path length increased from the early squat repetition ranges to the later squat repetition ranges. This was supported in a study that measured sway index after performing a fatiguing back squat protocol. It was found that the sway index increased from 0.37±0.03 before the fatiguing back squat protocol to 0.80±0.05 immediately after the fatiguing back squat protocol, which showed that fatigue increased postural sway (Thiele, 2015). Furthermore, fatigue increased AP sway and path length in a study that fatigued elite soccer players by having them play in a soccer match, showed increased postural sway velocity, with values increasing from 114.0±16.5 to 131.8±18.9 mm/s (Zemkova, 2009). The increase in postural sway after both the fatiguing back squat and soccer match protocols explains that the statistically significant increase in the net AP path length that was found provides evidence that subjects did fatigue during the 20 BWT squats. However, this was the only postural control variable that increased across the set. Although there was only limited evidence of fatigue, there were statistically significant increases in average GRFv absolute asymmetries and AP postural control variables shifting to an increased reliance on the dominant limb over the rep ranges. Therefore, even though there is a lack of strong support for fatigue over these repetition ranges, there is evidence that a potential change in technique due to subjects finding a comfortable form, over these repetition ranges causing a change in these metrics and further research is needed to explore these changes.

Repeatability

The study also aimed at measuring repeatability of the collected metrics. The average minimum and maximum GRFv along with AP and ML sway and path length %SI variables showed high repeatability with most Cronbach's alpha values during the phases and squat repetition ranges above 0.80. Plus, there were no more than 2 values for each of these metrics

67

that dropped below 0.80. Since these values are fairly high, it shows that they can be predictive of asymmetry values. Additionally, the normalized net ML and AP sway and path length metrics had most Cronbach's alpha above 0.80, which showed that these metrics can be predictive of normalized values. The normalized net maximum GRFv metrics did not have high Cronbach's alpha values in that all but one were below 0.432. Additionally, the normalized net minimum GRFv metrics did not have high Cronbach's alpha values in all but that were below 0.666. Thus, the normalized net maximum and normalized net minimum GRFv metrics are not very predictive and may not be useful for future assessments.

Limitations

Limitations of this study include the lack of exploring sex differences in changes in asymmetry and normalized values with reps since males were not analyzed. Males might change in the rate at which their asymmetries change with rep differently than females, potentially due to differences in strength and power (Ceroni, 2012). Additionally, the small sample size of 14 subjects limits the power of the statistics in the study. With more subjects, we might find more statistically significant increases in asymmetry and normalized metrics due to the decrease in population variance. Although, the sample size of this study had enough power to detect statistically significant differences to show that some subjects have changes in asymmetries over repetition ranges while others don't. This is proof that more reps might lead to find more false positives and false negatives. Also, the subjects were drawn from a relatively homogenous population in that they were all young, currently healthy, recreationally active women. Furthermore, EMG and motion data were not included in this study, limiting the analysis by not having more precise fatigue metrics or joint angle information. Additionally, this was a cross sectional study that did not collect injury data over the season in order to determine if our data

was able to properly determine injury risk and our study was unable to collect data on athletes in a fatigued state to compare against. This data also had about half of the subjects return for a repeat visit, so caution needs to be used when analyzing for repeatability.

Future Studies

Future studies would complement and improve this study by including more subjects, males, injured verses non-injured individuals, and athletes at differing levels of competition. Furthermore, the study design could include a more fatiguing protocol with the use of a more fatiguing functional movement such as the jump squat. Additionally, future studies could include a measure of self-reported fatigue. Lastly, the study could track subjects to see if they sustain an injury during the season after the data collection was performed and the data collection could be repeated during the middle and end of a season to track the athletes longitudinally.

Conclusion

In conclusion, as a population, average absolute GRFv asymmetries and relative AP sway and path length asymmetries were found to increase during each of the phases and across all repetition ranges of the BWT squat. Additionally, significant differences between repetition ranges that were found occurred during different phases of the BWT squat. Although only a few fatigue related metrics were collected, some limited evidence of fatigue was found. Furthermore, individual asymmetry data shows that although many subjects either sustained high or low levels of asymmetry across all repetition ranges, there were a few subjects that had low levels of asymmetry during the early squat repetition range that increased to high levels of asymmetry during the middle and late squat repetition ranges and a few subjects that had high levels of asymmetry during the early squat repetition range that dropped to low levels of asymmetry in the

middle and late squat repetition ranges. Differences were also found in responses across reps in

the down phase compared to the up phase. High repeatability was found in all asymmetry and

some normalized net metrics, showing that most of the metrics can be predictive. Therefore, it is

important to investigate each of the phases of the BWT squat for 10 to 12 BWT squats rather

than 3 to 5 in order to detect high levels of asymmetry and potentially fatigue and thus determine

risk for a lower limb injury. Future research is necessary to determine whether the 10 to 12

BWT squats are better at predicting injury than the prescribed 3 to 5 BWT squats.

REFERENCES

Atun-Einy, O. (2016). Asymmetrical motor behaviour as a window to early leg preference: a longitudinal study in infants 7–12 months of age. *Laterality: Asymmetries of Body, Brain and Cognition,* 21: 177-199.

Augustsson, J., Thomee, R., Linden, C., Folkesson, M., Tranberg, M., Karlsson, J. (2006). Single-leg hop testing following fatiguing exercise: reliability and biomechanical analysis. *Scand J Med Sci Sports,* 16: 111–120.

Bailey, C.A, Sato, K., Burnett, A., and Stone, M.H. (2015). Carry-over of force production symmetry in athletes of differing strength levels. *J Strength Cond Res* 29: 3188–3196.

Barber-Westin, S.D., Noyes, F.R. (2017). Effect of Fatigue Protocols on Lower Limb Neuromuscular Function and Implications for Anterior Cruciate Ligament Injury Prevention Training. *The American Journal of Sports Medicine*, 45: 3388-3396.

Barden, J.M., Kell, R.T., Kobsar, D. (2011) The effect of critical speed and exercise intensity on stroke phase duration and bilateral asymmetry in 200-m front crawl swimming, *Journal of Sports Sciences*, 29: 517-526.

Behan F.P., Maden-Wilkinson T.M., Pain M.T.G, Folland J.P. (2018) Sex differences in muscle morphology of the knee flexors and knee extensors. *PLoS ONE*, 13: 1-15.

Bell, D.R., Pennuto, A.P., Trigsted, S.M. (2016). The effect of exertion and sex on vertical ground reaction force variables and landing mechanics. *J Strength Cond Res* 30: 1661–1669.

Bennett, H., Davison, K., Arnold, J., Slattery, F., Martin, M., Norton, K. (2017). Multicomponent musculoskeletal movement assessment tools: a systematic review and critical appraisal of their development and applicability to professional practice. *J Strength Cond Res*, 31: 2903–2919

Bishop, C., Turner, A., Read, P. (2018) Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences*, 36: 1135-1144.

Bisson, E.J., Lajoie, Y., Bilodeau, M., (2014). The influence of age and surface compliance on changes in postural control and attention due to ankle neuromuscular fatigue. *Exp Brain Res*, 232: 837–845.

Bission, E.J., McEwen, D., Lajoie, Y., Bilodeau, M. (2011). Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance. *Gait & Posture,* 33: 83-87.

Bridgeman, LA, McGuigan, MR, Gill, ND, and Dulson, DK. (2018). Relationships between concentric and eccentric strength and countermovement jump performance in resistance trained men. *J Strength Cond Res* 32: 255–260.

Brown, A.M., Zifchock, R.A., Hillstrom, H.J. (2014). The effects of limb dominance and fatigue on running biomechanics. *Gait & Posture,* 39: 915-919.

Bourne, M.N., Opar, D.A., Williams, M.D., Shield, A.J. (2015). Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby Union. *The American Journal of Sports Medicine,* 43: 2663-2670.

Bullock, G.S. Brookreson, N., Knab, A.M., Butler, R.J. (2016). Examining fundamental movement compentency and closed-chain upper-extremity dynamic balance in swimmers. *Journal of Strength and Conditioning Research* , 31: 1544–1551.

Byrne, C., Eston, R. (2002) Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions, *Journal of Sports Sciences*, 20: 951-959.

Ceroni, D, Martin, XE, Delhumeau, C, and Farpour-Lambert, NJ. (2012). Bilateral and gender differences during single-legged vertical jump performance in healthy teenagers. *J Strength Cond Res*, 26: 452–457.

Clifton, D.R., Grooms, D.R., Onate, J.A. (2015). Overhead deep squat performance predicts Functional Movement Screen Score. *The International Journal of Sports Physical Therapy,* 10: 622-627.

Cook, G., Burton, L., Hoogenboom, B. (2006). Pre-participation screening: The use of fundamental movements as an assessment of function – part 1. *North American Journal of Sports Physical Therapy,* 1: 62-72.

Dauty, M., Dupre, M., Potriron-Josse, M., Dubois, C. (2007). Identification of mechanical consequences of jumper's knee by isokinetic concentric torque measurement in elite basketball players. *Isokinetics and Exercise Science* , 15: 37–41.

Dionisio, V.C., Almedia, G.L., Duarte, M., Hirata, R.P. (2008). Kinematic, kinetic and EMG patterns during downward squatting. *Journal of Electromyography and Kinesiology*, 18: 134–143.

Duke, S.R., Martin, S.E., Gaul, C. (2017). Preseason functional movement screen predicts risk of time-loss injury in experienced male rugby union athletes. *J Strength Cond Res*, 31: 2740-2747.

Evans, R. (1994). Illustrated essentials in orthopedic physical assessment. St. Louis, Missouri: Mosby.

Filipcic, A., Cuk, I., Filipcic, T. (2016). Lateral asymmetry in upper and lower limb bioelectrical impedance analysis in youth tennis players. *Int. J. Morphol.*, 34: 890-895.

Flanagan, E.P., Galvin, L., Harrison, A.J. (2008). Force Production and Reactive Strength Capabilities After Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training*, 43: 249–257.

Friedmann-Bette, B., Bauer, T., Kinscherf, R., Vorwald, S., Klute, K., Bischoff, D., Müller, H., Weber, M.A., Metz, J., Kauczor, H.U., Bärtsch, P., Billeter. R. (2010). Effects of strength training with eccentric overload on muscle adaptation in male athletes. *Eur J Appl Physiol*, 108: 821–836.

Frost, D.M. Beach, T.A.C, Callaghan, J.P., McGill, S.M., (2015). FMS scores change with Performers' knowledge of the grading criteria—are general whole-body movement screens capturing "dysfunction"? *Journal of strength and conditioning research,* 29: 3037-3044.

Gillies, E.M., Putman, C.T., Bell, G.J. (2006). The effect of varying the time of concentric and eccentric muscle actions during resistance training on skeletal muscle adaptations in women. *Eur J Appl Physiol* 97: 443–453.

Girard, J., Quigley M., Helfst, F. (2016) Does the functional movement screen correlate with athletic performance? A systematic review. *Physical Therapy Reviews*, 21: 83-90.

Greska, E.K., Cortes, N., Ringleb, S.I., Onate, J.A., Van Lunen, B.L. (2017). Biomechanical differences related to leg dominance were not found during a cutting task. *Scand J Med Sci Sports,* 27: 1328–1336.

Guilherme, J., Garganta, J., Graça, A., Seabra, A. (2015) Influence of non-preferred foot technical training in reducing lower limbs functional asymmetry among young football players. *Journal of Sports Sciences*, 33: 1790-1798.

Hammes, D., Fünten, D., Bizzini, M., Meyer, T. (2016) Injury prediction in veteran football players using the Functional Movement Screen™. Journal of Sports Sciences, 34: 1371-1379.

Haddas, R., Sawyer, S.F., Sizer, P.S., Brooks, T., Chyu, B.C., James, C.R. (2017). Effects of Volitional Spine Stabilization and Lower-Extremity Fatigue on the Knee and Ankle During Landing Performance in a Population With Recurrent Low Back Pain. *Journal of Sport Rehabilitation*, 26: 329 -338.

Hart, N.H., Nimpuius, S., Spiteri, T., Newton, R.U., (2014). Leg Strength and Lean Mass Symmetry Influences Kicking Performance in Australian Football. *Journal of Sports Science and Medicine*, 13: 157-165.

Hewett, T.E., Lindenfeld, T.N., Riccobene J.V., Noyes, F.R. (1999). The Effect of Neuromuscular Training on the Incidence of Knee Injury in Female Athletes. *The American Journal of Sports Medicine,* 27, 699-706.

Hirata, R.P., Arendt-Nielsen, L., Shiozawa, S., Graven-Nielsen, T. (2012). Experimental knee pain impairs postural stability during quiet stance but not after perturbations. *Eur J Appl Physiol*, 112: 2511–2521.

Hodges, S.J., Patrick, R.J., and Reiser II, R.F. (2011). Effects of fatigue on bilateral ground reaction force asymmetries during the squat exercise. *J Strength Cond Res*, 25: 3107–3117.

Hootman, J.M., Dick, R., Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train,* 42: 311-319.

James, C.R., Scheuermann, B.W., Smith, M.P. (2010). Effects of two neuromuscular fatigue protocols on landing performance. *Journal of Electromyography and Kinesiology,* 20: 667–675.

Jordan, M.J., Aagaard, P., Herzog, W. (2015). Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. *Scand J Med Sci Sports*, 25: 301–309.

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

Kerr, A.Y., Lincoln, A.E., Caswell, S.V., Klossner, D.A., Walker, N., Dompier, T.P. (2018). Epidemiology of National Collegiate Athletic Association Women's Lacrosse Injuries, 2009–10 Through 2014–15. *Journal of Sport Rehabilitation*, 27: 118-125.

Kiesel, K., Plisky, P.J., Voight, M.L. (2007). Can serious injury in professional football be Predicted by a preseason Functional Movement Screen? *North American Journal of Sports Physical Therapy,* 2: 147-158.

Kim, J.W., Kwon, Y., Ho, Y., Jeon, H.M., Bang, M.J, Jun, J.H., Eom, G.M., Park B.K., Cho, Y.B. (2014). Age–gender differences in the postural sway during squat and stand-up movement. *Bio-Medical Materials and Engineering,* 24: 2707–2713.

Kim, J.W., Kwon, Y., Jeon, H.M., Bang, M.J, Jun, J.H., Eom, GM., Lim, D.H. (2014). Feet distance and static postural balance: Implication on the role of natural stance. (2014). *Bio-Medical Materials and Engineering,* 24: 2681–2688.

King, A.C., Wang, Z. (2017). Asymmetrical stabilization and mobilization exploited during static single leg stance and goal directed kicking. *Human Movement Science,* 54: 182-190.

Kobayashi, Y., Kubo, J., Matsuo, A., Matsubayashi, T., Kobayashi, K., Ishii, N. (2010). Bilateral asymmetry in joint torque during squat exercise performed by long jumpers. *J Strength Cond Res*, 24: 2826–2830.

Lawson, B.R., T.M. Stephens II, D.E. DeVoe, R.F. Reiser II. (2006). Lower-extremity bilateral differences during step-close and no-step countermovement jumps with concern for gender. *J. Strength Cond. Res*. 20: 608–619.

Leal de Souza, L.M., Barros da Fonseca, D., Cabral H., Fernandes de Oliveira L., Vieira, T. (2017). Is myoelectric activity distributed equally within the rectus femoris muscle during loaded, squat exercises? *Journal of Electromyography and Kinesiology* 33: 10–19.

Lehance, C., Binet,J., Bury, T., Croisier, J.L., (2009). Muscular strength, functional performances and injury risk in professional and junior elite soccer players. *Scand J Med Sci Sports*, 19: 243–251.

Lessi, G.C., Serrao, F.V. (2015). Effects of fatigue on lower limb, pelvis and trunk kinematics and lower limb muscle activity during single-leg landing after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc,* 25: 2550–2558.

Lockie, R.G., Schultz, A.B., Jordan. C.A., Callaghan, S.J., Jeffriess, M.D., Luczo, T.M. (1993). Can selected Functional Movement Screen Assessments be used to identify movement deficiencies that could affect multidirectional speed and jump performance? *Journal of Strength and Conditioning Research,* 29: 195-205.

Lord, C., Ma'ayah, F., Blazevich, A.J. (2017). Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. *Scandinavian Journal of Medicine & Science In Sports,* 28: 1235-1243.

Maloney, S.J., Richards, J., Nixon, D.G.D., Harvey, L.J., Fletcher I.M., (2017). Do stiffness and asymmetries predict change of direction performance? *Journal of Sports Sciences*, 35: 547-556.

MateÂ-Muñoz J.L., Lougedo J.H., Barba M., GarcõÂa-FernaÂndez P., Garnacho-Castaño M.V., DomõÂnguez R. (2017). Muscular fatigue in response to different modalities of CrossFit sessions. *PLoS ONE*, 12: 1-17.

McCurdy, K., G. Langford, M. Doscher, L. Wiley, and K. Mallard. (2005). The effects of short-term unilateral and bilateral lower-body resistance training on measures of strength and power. *J. Strength Cond. Res*. 19: 9–15.

McDonald, A. C., Tse, C.T.F., Keir, P.J. (2016). Adaptations to isolated shoulder fatigue during simulated repetitive work. Part II: Recovery. *Journal of Electromyography and Kinesiology,* 29: 42-49.

McGrath, T.M., Waddington, G., Scarvell, J.M., Ball, N.B., Creer, R., Woods, K., Smith D. (2016). The effect of limb dominance on lower limb functional performance – a systematic review. *Journal of Sports Sciences*, 34: 289-302.

McGuine, T.A., Post, E.G., Hetzed, S.J. Brooks, M.A., Trisgted, S., Bell, D.R. (2017). A Prospective Study on the Effect of Sport Specialization on Lower Extremity Injury Rates in High School Athletes. *The American Journal of Sports Medicine,* 45: 2706-2712.

Mengarelli, A., Verdini, F., Cardarelli, S., Di Nardo, F., Burattini, L., Fioretti, S. (2018). Balance assessment during squatting exercise: A comparison between laboratory grade force plate and a commercial, low-cost device. *Journal of Biomechanics,* 71: 264-270.

Miranda, D. L., P. D. Fadale, M. J. Hylstyn, R. M. Shalvoy, J. T. Machan, B. C. Fleming. (2013). Knee Biomechanics during a Jump-Cut Maneuver: Effects of Sex and ACL Surgery. *Med. Sci. Sports Exerc.,*45: 942–951.

Mokha, M., Sprague, P.P., Gatens, D.R. (2016). Predicting Musculoskeletal Injury in National Collegiate Athletic Association Division II Athletes From Asymmetries and Individual-Test Versus Composite Functional Movement Screen Scores. *Journal of Athletic Training*, 51: 276–282.

Munger, C.N., Archer, D.C., Leyva, W.D., Wong, MA., Coburn, J.W., Costa, P.B., Brown, L.E. (2017). Acute effects of eccentric overload on concentric front squat performance. *J Strength Cond Res*, 31: 1192–1197.

Myers, C.A., Hawkins, D. (2010). Alterations to movement mechanics can greatly reduce. anterior cruciate ligament loading without reducing performance. *Journal of Biomechanics*, 43: 2657-2664.

Numata, H., Nakase, J., Kitaoka, K., Shima, Y., Oshima, T., Takata, Y., Shimozaki, K., Tsuchiya, H. (2017). Two-dimensional motion analysis of dynamic knee valgus identifies female high school athletes at risk of non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc*, 26: 442–447.

O'Reilly, M.A., Whelan, D.F., Ward, T.E., Delahunt, E., Caulfield, B.M. (2017). Technology in strength and conditioning: assessing bodyweight squat technique with wearable sensors. *J Strength Cond Res*, 31: 2303–2312

Overmoyer, G.V., Reiser, R.F. (2013). Relationships between asymmetries in functional movements and the star excursion balance test. *J Strength Cond Res,* 27: 2013–2024.

Paterno, M.V., Rauh, M.J., Schmitt, L.C., Ford, K.R., Hewett, T.E. (2012). Incidence of Contralateral and Ipsilateral Anterior Cruciate Ligament (ACL) Injury After Primary ACL Reconstruction and Return to Sport. *Clin J Sport Med*, 22: 116–121.

Porru, S., Calza, S., Arici, C. (2017). Prevention of occupational injuries: Evidence for effective good practices in foundries. *Journal of Safety Research,* 60: 53-69.

Radzak, K.N., Putnam, A.M., Tamura, K., Hetzler, R.K., Stickley, C.D. (2017). Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait & Posture,* 51: 268-274.

Razak, A.H., Zayegh, A., Begg, R.K., Wahab, Y. (2012). Foot Plantar Pressure Measurement System: A Review. *Sensors,* 12: 9884-9912.

Read, P.J., Oliver, J.L., De Ste Croix, M.B.A., Myer, G.D, Lloyd, R.S. (2016). Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players. *Sports Med*, 46: 1059–1066.

Reese, N.B., Bandy, W.D. (2002). Joint Range of Motion and Muscle Length Testing. W.B. Saunders: Philadelphia, Pennsylvania.

Roi, G., Bianchedi, D., (2008). The Science of Fencing Implications for Performance and Injury Prevention. *Sports Med*, 38: 465-481.

Sanford, B.A., Williams J.L., Zucker-Levin, A., Mihalko, W.M. (2016). Asymmetric ground reaction forces and knee kinematics during squat after anterior cruciate ligament (ACL) reconstruction. *The Knee,* 23: 820-825.

Sasaki, S., Koga, H., Krosshaug, T., Kaneko, S., fukubayashi. T. (2018). Kinematic analysis of pressing situations in female collegiate football games: New insight into anterior cruciate ligament injury causation. *Scand J Med Sci Sports*, 28: 1263–1271.

Severin A.C., Burkett B.J., McKean M.R., Wiegand A.N., Sayers M.G.L. (2017) Quantifying kinematic differences between land and water during squats, split squats, and single-leg squats in a healthy population. *PLoS ONE* 12: 1-15.

Small, K., McNaughton, L. R., Greig, M., Lohkamp, M., Lovell, R. (2009). Soccer Fatigue, Sprinting and Hamstring Injury Risk. *Int J Sports Med ,* 30: 573 – 578.

Steffen, K., Nilstad, A., Kristianslund, E.K., Myklebust, G., Bahr, R., Krosshaug, T. (2016). Association between Lower Extremity Muscle Strength and Noncontact ACL Injuries. *Medicine & Science in Sports & Exercise*, 16: 2082-2089.

Tee, J.C., Klingbiel, J.F.G., Collins, R., Lambert, M.I., Coopoo, Y. (2016). Preseason Functional Movement Screen component tests predict severe contact injures in professional rugby union players. *Journal of Strength and Conditioning Research,* 30: 3194-3203.

Thiele, R.M., Conchola, E.C., Palmer, T.B., DeFreitas J.M., Thompson B.J. (2015). The effects of a high-intensity free-weight back-squat exercise protocol on postural stability in resistance-trained males. *Journal of Sports Sciences*, 33: 211-218.

Trivers R., Fink B., Russell M., McCarty K., James B., et al. (2014) Lower Body Symmetry and Running Performance in Elite Jamaican Track and Field Athletes. *PLoS ONE,* 9: 1-9.

Vázquez-Guerrero J., Moras G., Baeza J., Rodríguez-Jiménez S. (2016). Force Outputs during Squats Performed Using a Rotational Inertia Device under Stable versus Unstable Conditions with Different Loads. *PLoS ONE* 11: 1-13.

Warren, M., Smith, C.A., Chimera, N.J. (2015). Association of the Functional Movement Screen With Injuries in Division I Athletes. *Journal of Sport Rehabilitation*, 24: 163-170.

Webster, K.E., Austin, D.C., Feller J.A., Clark, R.A., McClelland, J.A. (2015). Symmetry of squatting and the effect of fatigue following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 23: 3208–3213.

Webster, K.E., Wotherspoon, S., Feller, J.A., McClelland, J.A. (2013). The effect of anterior cruciate ligament graft orientation on rotational knee kinematics. *Knee Surg Sports Traumatol Arthrosc,* 21: 2113–2120.

Weeks, B.K., Carty, C.P., Horan., S. (2015). Effect of sex and fatigue on single leg squat kinematics in healthy young adults. *BMC Musculoskeletal Disorders,* 16: 271-280.

Wilke, J., Fleckenstein, J., Krause, F., Vogt, L., Banzer, W., (2016) Sport-specific functional movement can simulate aspects of neuromuscular fatigue occurring in team sports. *Sports Biomechanics*, 15: 151-161.

Zemkova, E., Hamar, D. (2009). The effect of soccer match induced fatigue on neuromuscular performance. *Kinesiology*, 41: 195-202.

APPENDICES

APPENDIX A

Human Subjects Approval

From: Tammy.Felton-Noyle@colostate.edu
Sent Date: Wednesday, October 04, 2017 13:55:16 PM
To: Jillian.Sirkis@colostate.edu, Raoul.Reiser@ColoState.EDU
Cc:
Bcc:
Subject: The following Protocol has been Approved: 15-5776H
Message:
The IRB has approved your protocol referenced below:

Protocol ID: 15-5776H
Principal Investigator: Reiser, Raoul

Protocol Title: Squatting and Hopping Functional Asymmetries
Review Type: EXPEDITED
Approval Date: September 29, 2017

This is not an official letter of approval. Your approval letter is available to you in the "Event History" section of your approved protocol in eProtocol. Note that specific information regarding the approval and any conditions of approval are available below the signature line in the footer of the approval letter.

IMPORTANT REMINDER: If you will consent your participants with a signed consent document, it is your responsibility to use the consent form that has been finalized and uploaded into the consent section of eProtocol by the IRB coordinators. Failure to use the finalized consent form available to you in eProtocol is a reportable protocol violation.

If you have any questions regarding this approval, please contact:

CSU IRB: RICRO_IRB@mail.colostate.edu; 970-491-1553
Evelyn Swiss: Evelyn.Swiss@Colostate.edu ; 491-1381
Tammy Felton-Noyle: Tammy.Felton-Noyle@colostate.edu; 491-1655

TO ACCESS THIS PROTOCOL, LINK TO:
https://csu.keyusa.net/

Health History and Activity Questionnaire

Squatting and Hopping Functional Asymmetries
(2017 - 2018)

Health History Questionnaire
(completed during recruitment interview)   Sex: **M** or **F**

Are you between the ages of 18-30 years?_____

DOB:_____

Are you healthy (have you been pain and injury free in upper and lower extremities and trunk, with full participation in exercise for the last month)?

_____

Are you comfortable exerting maximal levels of effort from the legs?

_____

Do you have now, or ever had, chronic low-back pain or scoliosis?

_____

Do you have any orthopedic or arthritic problems?

_____

Do you use any braces or orthotics during exercise?

_____

Do you have a balance disorder or taking any medication that affects your balance?

_____

Women only: Are you pregnant?

_____

Do you have any prior injuries or conditions of the upper and lower extremities or trunk that would cause you to favor one side of the body while performing otherwise symmetric tasks (broken bones, torn muscles and ligaments, a leg-length differential, etc.)?

_____

_____

_____

Do you regularly perform ground-based exercises that include squatting and jumping type activities?

_____ If yes, what types and approximately how often per week (in the last month)?

_____

_____

What other activities do you participate in and approximately how often per week?

_____

_____

What high school sports did you compete in (year started and level achieved)?

_____

_____

What sports have you competed in since high school (years and level)?

_____

_____

What is your current competitive athletic activity?

_____

_____

Ethnicity

(Optional):_____

Acceptable Subject?   Yes   or   No

Acceptable: When might we be able to schedule your lab visit and (optional) DXA scan?

_____

Unacceptable: Unfortunately you do not qualify for our current study. May we keep your name and contact information on file for future studies?

_____

_____

Additional Notes/Comments:

_____
_____
_____
_____
_____
_____
_____
_____

APPENDIX C

Consent Form

Consent to Participate in a Research Study

Colorado State University

TITLE OF STUDY: **Squatting and Hopping Functional Asymmetries**

PRINCIPAL INVESTIGATOR: Raoul F. Reiser II, PhD. Department of Health and Exercise Science. Director of the Clinical Biomechanics Laboratory. Contact project coordinator, Jillian Sirkis at (970) 491-7980 or Jillian.Sirkis@colostate.edu.

WHY AM I BEING INVITED TO TAKE PART IN THIS RESEARCH? *You are being asked to volunteer for this research because you are a healthy adult between the ages of 18-30 years with no current injuries (pain and injury free for the last month). You must also be free of any medical condition that affects balance or medication affecting balance, and free of current or chronic low-back pain or scoliosis. You must be regularly (on average twice a week for the last month) participating in activities that require jumping and squatting. You must be willing to perform jumping, squatting and standing tasks as well as range of motion and strength tests for the lower extremities. Note: many medications list the possible side effect of reduced balance, though you might not experience a problem and you would be fine to participate. If the medication causes you to feel dizzy, light-headed, unsteady, woozy, or like you are floating or spinning you should not participate. Typical medications you might encounter that affect balance are certain antibiotics and painkillers.*

WHO IS DOING THE STUDY? *This research is being performed by Raoul F. Reiser II, Ph.D. of the Health and Exercise Science Department. Dr. Reiser is interested in musculoskeletal biomechanics, specifically in relation to injury risk and performance. Trained graduate students, undergraduate students, research associates, or research assistants are assisting with the research.*

WHAT IS THE PURPOSE OF THIS STUDY? *It is well documented that asymmetries exist in the lower extremity (i.e., one leg is naturally favored over the other), and that these asymmetries may influence performance and injury risk. However, it is not well understood which screening methodologies may be predictive of such asymmetries, and how various movements in which these asymmetries exist relate to each other. The goal of this investigation is to clarify the relationship between screening methods and asymmetric force production of the lower extremities.*

WHERE IS THE STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST? *This research project will take place in the Clinical Biomechanics Laboratory located in Moby Arena on the CSU main campus. Your involvement will last roughly 1 hour. If you decide to return for a repeat visit, to help us determine the reliability of our measures, your involvement will double (2 hours total for both visits). However, a second visit is not required. We are also interested in how asymmetries during standing, squatting, hopping, and jumping relate to lower extremity*

muscle mass and bone lengths. These are measured with a DEXA scan. The DEXA machine uses x-rays to determine your body composition and bone mineral content. The DEXA scan requires you to lie quietly on a padded table while a small probe gives off low-level x-rays and sends them over your entire body. This test gives very accurate measurements of your body fat and bone mineral density. The DEXA scan is optional, taking roughly 30 minutes to complete.

WHAT WILL I BE ASKED TO DO? *If you agree to participate you will be required to do several trials of single and double leg standing, bodyweight squatting, and maximal effort hopping and jumping. During each of the trials you will have the forces under your feet measured. We will provide you with warm-up and practice of each task. We will give you rest between each to avoid fatigue. Height, weight, limb length and hamstring flexibility and strength will also be measured. There are no needles or other devices that will break the skin.*

ARE THERE REASONS WHY I SHOULD NOT TAKE PART IN THIS STUDY? *You should not volunteer for this study if you do not meet the criteria outlined above. You should not volunteer if you are unable to come to the laboratory well rested and free of fatigue and soreness. You must be able to exert maximal effort during the several tasks. Additionally, if you are a woman, you should not participate if you are pregnant. Regardless of gender, you should also not participate if you are uncomfortable with what you will be asked to do. All physical exertions are controlled by you.*

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS? *As with all physical activity, there is a risk for injury. The most likely risks associated with this study are muscle strains and pulls as well as muscle fatigue. If you land awkwardly, you are also at risk of joint injury, such as an ankle sprain. That fact that you are relatively fit, are familiar with the squat and jump, and that we will spot you and give you plenty of opportunity to warm-up and practice minimizes these risks. During standing trials we will also have a spotter beside you in the case you lose your balance. Furthermore, we suggest you not "lock" your knees when standing, as this can sometimes cause lightheadedness. Hamstring flexibility measures have you move your joints, not us. Hamstring strength is also under your control. You will be asked to slowly build to maximal exertion, hold it for a few seconds, then relax.*

You are also given breaks between each task to minimize risk for injury. If at any time you feel uncomfortable, pain, or are excessively tired, you should discontinue effort and tell the investigator. It is not possible to identify all potential risks in research procedures, but the researcher has taken reasonable safeguards to minimize any known and potential, but unknown, risks.

The risks associated with the optional DEXA are very low. The maximum radiation dose you will receive per scan is less than 1/3000th of the federal and state occupational whole body dose limit allowed to radiation workers. Put another way, you will receive less than 1.3 mrem from this scan and you already receive approximately 450 mrem per year from normal background radiation doses in Colorado. However, the more radiation you receive over the course of your life, the more the risk increases of developing a fatal cancer or inducing changes in genes. The radiation dose you receive from this scan is not expected to significantly increase these risks, but the exact increase in such risks is not known. There are no discomforts associated with this procedure.

WILL I BENEFIT FROM TAKING PART IN THIS STUDY? *While this study should provide useful information that may in the future provide useful information in understanding lower limb*

asymmetries, there are no current benefits to participation in this study. You will have the benefit of receiving full body composition testing via DEXA for free. Your body composition and bone mineral density results will be available to you at the end of involvement in the study. We are also happy to provide you with your other results if desired.

DO I HAVE TO TAKE PART IN THE STUDY? *Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.*

WHAT WILL IT COST ME TO PARTICIPATE? *There are no costs to participate in this study. However, if you are injured during the course of involvement, you will be responsible for medical costs beyond the emergency treatment. You must provide your own transportation to and from Moby arena.*

WHO WILL SEE THE INFORMATION THAT I GIVE? *We will keep private all research records that identify you, to the extent allowed by law.*

Your information will be combined with information from other people taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. You will not be identified in these written materials. We may publish the results of this study; however, we will keep your name and other identifying information private.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from your research records and these two things will be stored in different places under lock and key. You should know, however, that there are some circumstances in which we may have to show your information to other people. For example, the law may require us to show your information to a court. We may be asked to share the research files for audit purposes with the CSU Institutional Review Board ethics committee, if necessary. *The files containing information about you will be identified with a code, such as "FA01," where FA is short for Functional Asymmetry and 01 is a subject number. Upon completion of data collection and verification of results, the list linking your name to the code will be destroyed.*

CAN MY TAKING PART IN THE STUDY END EARLY? *Your participation in the study may end early if you are unable to perform the tasks required of the study.*

WILL I RECEIVE ANY COMPENSATION FOR TAKING PART IN THIS STUDY? *There is no monetary compensation for your involvement in the study.*

WHAT HAPPENS IF I AM INJURED BECAUSE OF THE RESEARCH? *The Colorado Governmental Immunity Act determines and may limit Colorado State University's legal responsibility if an injury happens because of this study. Claims against the University must be filed within 180 days of the injury.*

In light of these laws, you are encouraged to evaluate your own health and disability insurance to determine whether you are covered for any physical injuries or emotional distresses you might

sustain by participating in this research, since it may be necessary for you to rely on your individual coverage for any such injuries. Some health care coverages will not cover research-related expenses. If you sustain injuries, which you believe were caused by Colorado State University or its employees, we advise you to consult an attorney.

WHAT IF I HAVE QUESTIONS? *Before you decide whether to accept this invitation to take part in the study, please ask any questions that might come to mind now. Later, if you have questions about the study, you can contact the investigator, Raoul F. Reiser II, Ph.D. at 970-491-6958. If you have any questions about your rights as a volunteer in this research, contact the CSU IRB at: RICRO_IRB@mail.colostate.edu ; 970-491-1553. We will give you a copy of this consent form to take with you.*

This consent form was approved by the CSU Institutional Review Board for the protection of human subjects in research on (Approval Date).

Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing 3 pages.

_____   _____
Signature of person agreeing to take part in the study   Date

_____
Printed name of person agreeing to take part in the study

_____   _____
Name of person providing information to participant   Date

_____
Signature of Research Staff