Fatigued Stability in High School Athletes

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ABSTRACT

Purpose/Significance: Dynamic postural stability is needed for quick change of direction and jumping during sport. Reduced postural stability in athletes is associated with injury. Studies of collegiate athletes show the ability to maintain postural stability is compromised when fatigued. Less is known about fatigue effects in high school athletes. The purpose of this research was to investigate high school athletes to determine if fatigued postural stability declines. **Methods**: 260 high school (injury free) athletes participating in basketball, baseball/softball, lacrosse, soccer or track were recruited. Postural stability testing occurred using the Lower Quarter Y Balance Test (YBT-LQ) prior to, and after fatigue induced by sport specific training, designed by the team coach during a typical practice session. The YBT-LQ measured reach distances of the moving leg in 3 directions during single leg stance of the non-moving leg using standardized procedures with athletes wearing their sport shoes. Fatigue was defined as a level 14 on the Borg Rating of Perceived Exertion. **Findings:** Hypothesis testing did not find a reduction in fatigued postural stability except for clinically unimportant change in the anterior direction. Male and female adolescent athletes performed similarly indicating no sex difference in fatigued postural stability. Only lacrosse athletes showed reduced reach distance when fatigued indicating partial support of hypothesis 3. Another outcome of the study is the creation of normative fatigue data for adolescent athletes participating in 6 sports at 7 schools in Ohio. **Implication**: This study begins to answer the call for population specific normative data sets of postural stability. It also adds to the body of knowledge about fatigue induced postural stability that is age, sex and sport specific. A limitation of this study's findings is the possibility that coach led practice sessions did not induce enough fatigue to effect postural stability compared to fatigue induced during actual play. Key Words: postural stability, fatigue, adolescent athlete.

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Chapter One

Background

"Injuries are a part of the game. Every athlete knows that". Unfortunately, this quote attributed to Damian Lillard (Lillard, 2019) is becoming more and more true for our youth athletes. The National Federation of State High School Associations reports almost 8 million adolescents participated in an organized high school sport during the 2017-18 year, the last available data prior to Covid-19 ceased sport participation at high schools (NFHS, 2019). Engaging in a team sport provides physical, social and psychological benefits for adolescents (Gagliardi et al., 2020; Gardner et al., 2016; Moeijes et al., 2018; Mossman et al., 2021). However, a drawback to participating on a competitive sport team is the risk of physical injury during sport activity.

A recent epidemiology study of high school athletics found that 17 million injuries were reported to the High School Reporting Information Online (HSRIO) surveillance system from 2006 – 2019 (Ritzer et al., 2021). This surveillance system contains nationally collected information about injuries that occurred during football, wrestling, girls and boys soccer, basketball, volleyball and baseball/softball. Ninety-two percent of the injuries were classified as an acute injury and 8% classified as an overuse injury. The leg was the most frequently injured extremity for both acute and overuse diagnoses. Ligament sprains made up 32% of the acute injuries. Muscle strains (23.3%) and tendonitis (23.2%) were the 2 most commonly diagnosed overuse injuries. (Ritzer et al., 2021) reports that both boys and girls had more acute than overuse injury, and girls had more injuries than boys. The HSRIO reports that acute injuries often result in longer time loss from play (1-3 weeks) or inability to participate for the rest of the play season, as compared to overuse injury (< 1 week).

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Acute and overuse injuries both occur when joint structures and muscles are overloaded beyond their structural limit. Loss of frontal, sagittal or horizontal plane stability in the leg have all been found to predict serious non-contact ligament injury in both the knee and ankle (Boden et al., 2010; McGuine et al., 2000; Wang et al., 2006; B. Yu & Garrett, 2007). The ability to stabilize posture and movement to avoid overloading leg structures depends on an integrated functioning of the musculoskeletal and the neurologic systems (Iqbal, 2011; Sousa et al., 2012). The neurologic system needs to process sensory input to provide facilitatory and inhibitory control, and the muscular system must provide adequate strength and endurance to produce the exact magnitude of force at the exact moment needed. Without this neuromuscular integration, excessive tensile, compressive and torsional stresses can overload musculoskeletal tissues. Athletic activities typically use ballistic motions that are often at end range of musculoskeletal tissue tolerance increasing the potential for overloading tissues. Inadequacy of either the muscular or the neurologic system can result in the postural instability that creates excessive loads and injury.

Fatigue of muscles is one mechanism known to place an athlete susceptible to postural instability even in healthy athletes (Abdelkader et al., 2021; Baghbaninaghadehi et al., 2016; Pau et al., 2014; Reimer & Wikstrom, 2010; Salavati et al., 2007). The investigation of fatigue effect on sport performance has been going on for decades (Benjaminse et al., 2008; Ellenbecker & Roetert, 1999; Kawabata et al., 2000). Unfortunately, most of the research conducted did not include the youth athletic population. It has been determined that adolescent age athletes are still developing sensorimotor function needed for postural stability and in fact, some sensorimotor functions regress at puberty onset and recover to adult level at maturity (Quatman-Yates et al., 2012). It is suspect to expect that fatigue would affect adolescent athletes similarly to adults.

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Statement of the Research Problem

High school sports such as track, basketball and soccer requires the athlete to perform running, jumping and quick changes of direction. All of these activities depend on adequate dynamic postural stability to perform the maneuvers without overloading lower extremity joints and muscles. Previous research has shown that lack of postural stability is a valid predictor of sport injury (McGuine et al., 2000; Wang et al., 2006). Studies of athletes have shown that the ability to maintain postural stability is compromised when the neuromuscular system is fatigued (Abdelkader et al., 2021; Bond et al., 2020; Lacey & Donne, 2019; Pau et al., 2016; Reimer & Wikstrom, 2010). Neuromuscular fatigue is suspected as a contributor to musculoskeletal injury due to timing of most injuries occurring later in games (Dvorak, J et al., 2011; Ekstrand, J et al., 2011).

A problem with using current knowledge about fatigue and sport injury is that most of what we know has basis on studies of collegiate and professional athletes or healthy adults. This knowledge may or may not be applicable to the youth athlete defined as those less than 18 years old. An additional problem is that these studies induced fatigue using standardized laboratory or functional protocols such as interval running rather than sport specific fatiguing tasks simulating actual sport maneuvers. Sport injury prevention programs for youth athletes need to be informed by knowledge specific to this aged population while engaging in fatiguing activities typically performed during the sport they play.

A third problem with what is known about postural control, fatigue and sport injury is that the studies used measurement devices not available, nor easily used by school sport personnel. Earlier studies typically used laboratory equipment such as force plates, isokinetic devices or motion capture videography. More recent studies have utilized a device for

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measuring postural stability which is both accessible and easily trained for use by a school's sport personnel. The Y-Balance Test^{TM} for the lower quarter (YBT-LQ) is a simple to assemble, portable device which can be used at the playing field to monitor athlete performance. The YBT-LQ measures the ability to maintain single leg stance (SLS) while postural stability is challenged by movement of the non–weight bearing leg. Moving this leg adds a dynamic component to the test rather than being a measure of static stability. Most sports require unilateral standing with opposite leg movements like when kicking and changing directions while running.

There is literature supporting the reliability and validity of the YBT-LQ for measuring postural stability. Once again, a problem associated with this psychometric evidence is that the YBT-LQ measured postural stability data were mostly gained from testing of collegiate and professional athletes or healthy adults. This is true for both non-fatigued and fatigued postural stability. There is one study with a large sample size of high school athletes but the other studies with youth athletes have small sample sizes or are limited to investigating athletes of one or two sports (L. J. Smith et al., 2018). More youth athlete data collected via the YBT-LQ is needed so that an adequate quantity of data are available for establishing normative parameters for postural stability in high school age athletes. Normative data that are the most useful are population specific and stratified by age, gender and sport.

Rationale for the Study

Normative data for dynamic postural stability can be used for preseason screening to inform training needs and for developing injury prevention programs. The YBT-LQ measures single leg stance dynamic postural stability when the athlete moves the other leg in 3 directions (anterior, posteromedial & posterolateral) as far as possible without loss of stability. EMG

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studies have identified the hip, knee and ankle muscles most active for each reach direction. (Kaur et al., 2022) If an athlete has reach distances less than the norm for his/her age and body height, gender and sports participation, pre-season work out sessions can be individualized to focus on the performance of muscles corresponding to a particular reach direction. Performance on the YBT-LQ tool requires neuromuscular control to prevent loss of postural stability when reaching with the non-stance leg in multiple directions. Establishing typical reach distances that are sport specific can inform the development of neuromuscular focused prevention programs aimed at reducing or preventing sport specific injuries. Program developers would report the reach distance an athlete is expected to reach using good balance and body control so that joints and muscles are not overloaded by poor postural stability.

Another use of normative data is for return to sport decisions after an injury. In the absence of normative data, the criteria for return to sport after a leg injury is often when the healing leg can perform on a standardized task at some percentage of the non-injured leg, typically 90 percent. This criterion could still be used by specifying that the performance level the athlete needs is informed by his non-injured leg performance but within the normative range established by the YBT-LQ. An added value would be to have the normative data for non-fatigued and fatigued status which can further aid health care providers, athletic trainers (ATC), coaches and the athlete/parent in making return to sport decisions for youth athletes.

Utilizing the YBT-LQ device to establish normative data has a two-fold benefit. First, the normative data will be established using a measurement tool that can be used at the playing field during an actual sporting event or practice session. This means the normative data can be compared to ‘at the moment’ data collected from a healing athlete if s/he develops a problem during play or practice. The comparison of current status to normative data can determine if the

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athlete should cease activity for the day. It also means that performance issues can be quantified 'at the moment' the ATC or coach notices a reduction in performance of non-injured athletes. This identification of reduction in performance of non-injured athletes may suggest a need for practice or game play breaks to recover from fatigue and prevent injury.

A third benefit of using the YBT-LQ to establish fatigued normative data is that it enhances the validity of using the data. In validity studies, the testing of dynamic postural stability can occur field side using a fatigue protocol that is typical of practice session training and actual sport play. Sport specific fatigue is the best type of fatigue data for establishing risk of injury relationships, one of the most important uses of fatigue data (Benjaminse et al., 2008; Pau et al., 2014; Wilke et al., 2016).

A further benefit of using the YBT-LQ at field side involves improving the feasibility for conducting this study. The methodology for this study involves collecting measurements of postural stability when fatigue is induced by participating in training activities required by the coach at the field site. This involves testing the athletes very soon after stopping exertion so that whole body fatigue is maintained. Having the testing tool set up field side will enable the fatigued testing to occur within 4 minutes of stopping exertion. Four minutes is the amount of time used in prior fatigue studies and well less than the 10 minutes identified as short term fatigue recovery time (Johnston et al., 2018). Additionally, doing the testing nearby the practice field will reduce the time athletes are absent from the practice session. Reducing the interruption of the coach's training activities will likely make the coach more supportive of the study.

The benefits stated here for establishing both non-fatigued and fatigued normative data provide the rationales for this dissertation research. The most important rationale being that the

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results from the research may aid in reducing or preventing sports related injuries in high school athletes.

Purpose of the Study

The general purpose of this study is to add to the body of knowledge about dynamic postural stability in youth athletes participating in school organized competitive sports. Additional data and confirmation of data from the few studies with youth athletes is needed. The specific purpose is to provide both fatigued and non-fatigued postural stability data that can be used to reference typical performance (normative data) of both female and male youth athletes participating in common high school sports.

Research Questions and Hypotheses

1. Is there an effect of fatigue on the ability of youth athletes to maintain postural stability during dynamic SLS?

    Hypothesis 1: There will be no difference between pre-fatigue and fatigued reach distances for all three reach directions and composite scores.

2. Does fatigue challenge the postural stability of males and female athletes equally?

    Hypothesis 2: Female participants will have less fatigue effect on postural stability than the males.

3. Do youth athletes playing a specific sport experience fatigued SLS postural stability differently than youth athletes from other sports?

    Hypothesis 3: There will be no differences in fatigued and non-fatigued reach distances based on sport participation.

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Research Design

The methodology is a quasi- experimental, non-randomized pre-post design. The independent variable is fatigue and the dependent variable is postural stability. The collection of pre-fatigue testing allows the identification of normative data for youth athletes by gender and sport. The post-fatigue testing allows for the testing of fatigue effect by gender and sport participation. Sampling was by convenience for identifying the school where athletes were recruited. Sport team sampling at each participating school was also by convenience. Non-random sampling of volunteer athletes from the team occurred once the schools and sport teams were identified.

Limitations of the Research Design

Use of a pre-post design without a control group cannot exclude other reasons than the intervention for the results if an effect of fatigue on postural stability is found. In this study, neuromuscular learning effects of the testing procedure could explain the findings rather than fatigue effect (Ellenbecker & Roetert, 1999). To avoid confounding, athletes practiced testing procedures prior to data collection. The practice was completed according to the guidelines provided by the YBT-LQ developer and other researchers who determined the inter and intra-rater reliability for using the YBT-LQ to measure SLS dynamic postural control (Hertel et al., 2000; P. Plisky et al., 2021; Shaffer et al., 2013).

Definition of Terms

Postural stability: "Postural stability is the ability to sustain the body in equilibrium by maintaining the projected center of mass within the limits of the base of support. It is the ability to control the body position in space for the purpose of movement and balance." (Heebner et al., 2015; Woollacott & Shumway-Cook, 2002)

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- *Static postural stability*: ability to maintain a steady standing posture over a static base of support
- *Dynamic postural stability*: ability to transfer and control the projection of one's center of mass over a base of support while transitioning from a dynamic to static state

Neuromuscular Fatigue (NMF):" Repeated or sustained muscular contraction can result in a reduction in the maximal voluntary force muscle/s can produce. The reduction in force output produced either at the peripheral or central levels can be detected up to 48 hours or longer". (Alba-Jiménez et al., 2022)

Single leg stance (SLS): "Unipedal standing; standing on one leg with postural stability

Perceived exertion (physical): How hard you feel like your body is working. It is based on the physical sensations a person experiences during physical activity, including increased heart rate, increased respiration or breathing rate, increased sweating, and muscle fatigue" (*Perceived Exertion (Borg Rating of Perceived Exertion Scale) | Physical Activity | CDC*, 2022).

Y-Balance Test- Lower Quarter (YBT-LQ):" A tool to test neuromuscular control at the limits of stability" (P. Plisky et al., 2021)

Summary

Musculoskeletal injury in youth athletes is a growing phenomenon as trends in sport play result in year round sport specialization. Neuromuscular function must be adequate to maintain the postural stability needed to avoid excessive physical stress on joint and muscle tissue, and prevent injury. Neuromuscular function is known to decline in the presence of fatigue that occurs during sport practices or play (Abdelkader et al., 2021; Bourara et al., 2022; Paillard, 2012; Wilke et al., 2016). However, population specific gaps in knowledge about fatigue induced reduction in dynamic postural stability have been identified. The results of this

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investigation will begin to fill in the gaps related to fatigue effects specific to youth athletes. The methodology in this study will allow stratification of the results by gender and sport participation for this population of athletes. Knowledge gained from this study has potential to help health care professionals, school sport personnel and the athlete and his/her parents make decisions about sport participation.

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Chapter Two

Musculoskeletal Injury in Athletes

As previously noted, Ritzer et. al. (2021) reported the most recently available (2006-2019) injury findings from the High School Reporting Information Online (HSRIO) surveillance system. This surveillance system collects athletic injury data from a nationally representative sample of US high schools. The injury report provides rate and type of injury by participation in 9 high school sports. For non-contact injuries, ninety-two percent of the injuries were classified as acute injury and 8% classified as an overuse injury. The leg was the most frequently injured extremity for both acute and overuse diagnoses. Ligament sprains made up 32% of the acute injuries. Muscle strains (23.3%) and tendonitis (23.2%) were the 2 most commonly diagnosed overuse injuries. The HSRIO reports that acute injuries often result in longer time loss from play (1-3 weeks) or inability to participate for the rest of the play season, as compared to overuse injury (< 1 week).

Sports injuries in athletes can occur from traumatic contact with another player or piece of equipment. Non-contact injuries also occur and there are many theories for why. Theories include extrinsic factors such as playing surface, equipment and weather. Theories also include intrinsic factors specific to the athlete and many have been proposed to be able to predict injuries. Intrinsic factors include anatomic configuration (ex: intercondylar notch size, tibial plateau slope, pronated foot), biomechanical factors (ex: range of motion, strength, flexibility, neuromuscular control), overuse of musculoskeletal tissues without adequate recovery time, physiologic (ex: female hormone levels, BMI, less than 14 year old) and genetic factors (ex: personal healing process, leg dominance and family history) (DiFiori, 2010; Pfeifer et al., 2018; Prieto-González et al., 2021)

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According to an HSRIO summary report for the 2018 -2019 year (Comstock & Pierpoint, 2019) , the ankle was the most injured body area (21%) followed by the knee (14%), then the hip/thigh (10%). The ankle injuries occurred mostly to the anterior talofibular ligament (71%). The most commonly injured knee tissue was the medial collateral ligament (28%), followed by the anterior cruciate ligament (22%) and meniscus (22%) and patellar tendon (21%). There were no specific structures noted for the hip and thigh, and muscle injury is not identified by specific muscle, only listed in the sprain/strain category. Overall, surgery was required for 6.4% of the injuries sustained. Re-occurrence of injury in a same tissue occurring in the same academic year was 3% for those that occurred during competition and 4% for those occurring during practice sessions.

Brant et. al (2019) (Brant et al., 2019) looked at HSRIO data for sports that typically had both boys and girls teams such as basketball, soccer, baseball/softball, etc. to investigate for gender differences in sport injury in high school athletes. These authors report the relative risk of injury was not very different among the genders for a sport type and in general, neither was the mechanism of injury. What was different was the severity of the injury with girls requiring more medical imaging with an MRI and greater number of medical disqualifications for the remaining season than boys. The HSRIO report provides injury data by sport also. Injury highlights for the sports investigated in this dissertation study are now provided.

Injury by sport – soccer

Behind head concussions, the HSRIO reports the hip and thigh are the most injured areas of the body (17%) in male soccer players. Following the hip/thigh are the ankle (16%) and knee (13%). The bulk of the injuries are listed as sprains and strains. Female soccer players injure the ankle most frequently (24%) which includes both acute and overuse injury. The knee (16%) and

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hip/thigh (14%) follow in order of frequency. Defending and ball handling/dribbling are the team positions related to the most injuries in both male (26%) and female (23%) players. An epidemiology study of soccer injury in high school players reports about a quarter of all injuries were to muscle (Sentsomedi & Puckree, 2016). These authors explain that ball handling and defending (as compared to goalkeepers and strikers), require running with quick changes of direction with frequent accelerations/decelerations, thus explaining the most injured area for males. Actions of changing direction and deceleration place high loads on hip and thigh muscles. In soccer, the hamstring and hip adductor muscle groups are the most vulnerable to these loads (Distefano et al., 2018). The majority of ankle injuries sustained by female high school soccer players occurred when the body was rotated around a planted foot which occurs during a quick change of direction (A. J. Nelson et al., 2007) .

Injury by sport – basketball

According to the HSRIO data, ankle injuries are the most frequently injured body area for both male (42%) and female (29%) high school basketball players followed by the knee and then hip/thigh in both genders. A 5 year epidemiology study ending in 2014 reports ankle injury was as likely to occur during practice as during competition and this trend continues with the most recent HSRIO data (Clifton et al., 2018; Comstock & Pierpoint, 2019).

Interestingly, knee injuries make up 8% in males but 16% in females showing an injury proportion ratio (females to males) of 4.61. This pattern of disproportionate number of female knee injuries in basketball is confirmed in a recent meta-analysis of ACL injury in adolescent athletes (Bram et al., 2021). Basketball requires running and quick change of direction and in addition, jumping and landing. A basketball player often jumps with both feet off the ground,

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landing off balance with a twisting motion to change direction during rebounding. An analysis of videos taken of collegiate and professional athletes who sustained an ACL injury found the non-contact knee valgus collapse that occurred at the time of injury looked "strikingly similar to the collapses seen in situations with direct blows to the lateral knee" (Krosshaug et al., 2007). A recent meta-analysis reports that injury prevention programs specific to the youth athlete population are more effective in preventing basketball injury if jump training exercises are included (Stephenson et al., 2021).

Injury by sport – baseball/softball

Baseball and softball both had more upper extremity injuries than lower extremity, according to the 2019 HSRIO data. However, both males and females experienced a significant number of injuries to the legs. Hip/thigh injuries were the most common in males at 15%, knee injury at 8% and ankle injury representing 5%. For females, the most injured area is the ankle (10%), then knee (9%) and hip/thigh is 8%. Both the prior HSRIO report of softball data from 2005-2014 and the 2019 HSRIO report identify fielding and running bases as the most frequent activities for injury to occur in female softball players (Comstock & Pierpoint, 2019; Wasserman et al., 2019). For male baseball players, the HSRIO 2019 report identifies the same activities of fielding and running bases to cause the most injuries behind pitching. Pitching injuries are likely to be upper extremity related although the HSRIO data does not separate the injury data into upper and lower extremity. Another study alerted that leg injuries that occur when running bases are the leading cause of being medically disqualified for the season in both baseball and softball youth players (Brant et al., 2019). An epidemiology study of collegiate baseball players also found outfielders had higher rates of leg injuries than other team positions, and added that hamstring injury was the most common leg injury in both fielders and when base running

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(Hartnett et al., 2022). This same study suggests the forceful plantarflexion of the ankle to initiate a ballistic take off for base running explains ankle Achilles' tendon injuries in baseball players.

The only other study specific to leg injuries in high school baseball or softball players besides those analyzing HSRIO data, analyzed emergency room data (Farooqi et al., 2021). As expected, this study found serious injury was usually caused by contact with another player or ball. But, it also reports serious soft tissue sprains & strains are the most common diagnosis for female outfielders not involved in a contact injury. Additionally, softball players are almost twice as likely as baseball players to receive an MRI indicating the ER physician's concern for a serious musculoskeletal tissue problem.

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Injury by sport – lacrosse

The annual 2019 HSRIO report on the nine most common high school sports did not include high school lacrosse injury data. In 2018, Warner et. al. used HSRIO data from 2009-2016 and reported that similar to other sports, soft tissue injury of muscle and ligaments is the most commonly injured tissue in lacrosse players (Warner et al., 2018). These authors explained that the approach phase when making a lacrosse shot places a high load on musculoskeletal tissue as the athlete does a quick deceleration on a planted leg to set the shot. This sport also requires running acceleration and deceleration during quick change of directions to follow the ball. Another publication in 2019 confirmed the Warner et al findings, and in addition, reported the injury rates didn't vary based on school size (Pierpoint et al., 2019). This is in contrast with findings that injury rates in some other sports varied with smaller schools having more injuries (Clifton et al., 2018; Distefano et al., 2018). School size is used to promote equalization of

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ability of the high school players on teams competing with each other. It is thought that smaller schools have less talent to choose from so may have less skilled athletes. This information seems to indicate injury from lacrosse playing is unrelated to skill and even those with more skill get injured.

In 2015, lacrosse injuries to the knee required surgery more often than any other male sport no matter if the injury was from a contact or non-contract mechanism, and this held true for female players except for cheerleading (Vincent et al., 2015). Another study reports that girls had higher knee injury rates than boys in each of the 20 sports included in their epidemiology study except lacrosse (Swenson et al., 2013). The above sport injury data for high school lacrosse indicates injuries are often of a serious nature (requiring surgery) and occur in any skill level athlete whether male or female.

Injury by sport – track & cross country

Like lacrosse, the annual 2019 HSRIO report did not include high school track or cross country injury data. The most recent HSRIO data available for high school athletes involved in hurdling, sprints, distance running and relays was published in 2016 (Pierpoint et al., 2016). This report was the first to document injuries in high school track athletes and has not been repeated using HSRIO data. The 2016 findings identify a low injury rate in track athletes compared to other high school sports. None-the-less, during the 5 years of the data analysis, there were 2485 injuries reported. These would represent more severe injuries warranting reporting to the HSRIO system by a school ATC because reporting was limited to time loss injury. Muscle strains of the thigh was the most common injury in both females (25%) and males (33%). Ankle sprain was the second most frequent injury for females (9%) and the third

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for males (6%). Hip muscle strains, knee tendinitis and shin splints were other injuries reported with incident percentages in the 3%-7% range.

While the injury rate for high school track and cross country athletes is low, track is the second most popular sport for boys and the first for females so shear volume makes inquiry into the causes of injury important (NFHS, 2019). A summary of emergency room visits documented by the National Electronic Injury Surveillance System database reports track and field visits increased from 16,000 to 27,000 from 2008 to 2018 (Caldwel et al., 2022). The most common injury diagnosis was soft tissue sprain/strain at 40% involving the lower extremity (52%) compared to the trunk and arms. An epidemiology study of collegiate athletes specific to cross country identified overuse injury as the majority of injuries in this population (Kerr et al., 2016). Consistent with this, Brant et. al. (2019) identified overuse injuries as the most common type in sports without player to player contact, and specifically categorized track and cross country injury in the overuse/chronic category (Brant et al., 2019).

Causes of injury

Biomechanical control

Early investigations into the causes of injury focused on the biomechanics of postures and movements of the injured body area. For example, in a summary article Boden et al. (2010) reported a sagittal plane posture of reduced knee flexion during jump landing which was consistent across studies as a risk factor for ACL tears (Boden et al., 2010). These authors also report frontal plane knee valgus position is implicated as a risk factor for ACL injury as is an externally rotated lower extremity. Knee valgus and external rotation occur during change of direction maneuvers in sports such as soccer and lacrosse as well as during jump landing in

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sports like basketball. Early injury investigations looked toward explanations such as limited range of motion, strength imbalances and joint instability as causes for the improper biomechanics. Ankle sprain is a similarly high frequency injury diagnosis. As with studies of ACL risk factors, early investigators focused to biomechanical postures of the foot (pronation) and ankle (plantarflexion with internal rotation) as predisposing to ankle sprains, and looked toward improper passive and active joint functions as contributing toward these postures (Beynnon et al., 2002; Chan et al., 2010).   Even though training programs focused toward resolution of aberrant biomechanics such as pes planus, hindfoot inversion and restricted ankle motion found in these early studies, athletic injuries continued.

Neuromuscular control

Attention in the past 20 years has been toward investigating the neuromuscular control needed in the lower extremity kinematic chain and trunk to avoid injurious leg postures. Control of unwanted postures and motions requires the integration of active muscle function and passive restraint of non-contractile tissues in multiple joints. This integration requires the reception by the CNS of joint position and muscle length sensation followed by an accurate interpretation of this information by the nervous system so that motor planning for a posture or movement is accurate (Sousa et al., 2012; Woollacott & Shumway-Cook, 2002). This planning must then be implemented via motor output so that the right amount of force is provided by muscles at the right time to maintain the postural stability required. Wikstrom et al (2006) cautioned against the return to sport of injured athletes whose neuromuscular functioning was not adequate to withstand the forces created in lower extremity joints during cutting and jump landings common in sports (Wikstrom et al., 2006). Without adequate neuromuscular function, the postural

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stability needed to maintain optimal leg posture and movement cannot occur. Joint and muscle tissue become overloaded when leg postures and movements place these structures at the limits of their structural tolerance. In individual research and systematic reviews with meta-analysis studies, neuromuscular function was consistently identified as important for maintaining the postural stability needed for preventing musculoskeletal injury in athletes (Dingenen et al., 2016; Kobayashi et al., 2016; Pfeifer et al., 2018; P. Yu et al., 2022).

Postural stability

To maintain postural stability, the center of mass (COM) must stay within the base of support (BOS). Iqbal (2011) identifies the convergence of the body's center of mass (COM) and center of pressure (COP) to be important for maintaining static and dynamic postural stability (Iqbal, 2011). The center of mass refers to the center of gravity of the whole body. The center of pressure refers to the ground reaction force distribution vertical from the BOS. The COM can keep a distance of 5 cm relative to the COP and static postural stability will be maintained. Iqbal explains the concept of COM velocity control that is needed for dynamic postural stability. The velocity of movement of the COM toward the BOS limits must be managed to keep the COM within 2.5 cm of the COP relative to the BOS, at the instant of foot contact. If the neuromuscular systems do not function well enough to control the COM velocity, the 2.5 cm distance will be exceeded and dynamic postural stability will be lost. Reduced dynamic postural stability has been identified in injured athletes participating in many sports (Beynnon et al., 2002; Mokha et al., 2016; Wang et al., 2006; Witchalls et al., 2012; P. Yu et al., 2022).

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Measurement of Postural Stability

Measurement of postural stability in athletes has evolved with time. An excellent summary of the history of postural stability measurement is provided by Sell et. al. (Sell, 2012) . Early research measured body sway via COP movement using a force plate while the athlete stood in bilateral or unilateral stance under conditions of eyes open and eyes closed. The addition of perturbations to the athlete or the supporting surface gained more knowledge about the body's attempts to maintain static postural stability. However, Sell (2012) reports the studies of static posture measurement were often contradictory in regards to predicting injury. The next evolution involved athletes re-establishing static posture after jumping or landing on the force plate which researchers termed measuring dynamic postural stability. Sell's hypothesis back in 2012 was that static measures could not adequately identify risk factors of the moving athlete. His own study found a lack of correlation between static and dynamic measures of stability when the same athlete did a side to side jump on to the force plate vs static stand on the force plate. The measurement of dynamic postural stability is now the standard for research attempting to establish injury prediction models.

Measures of dynamic postural stability using a force plate are often augmented by videography where a video of the person moving can be coordinated with force plate data. This process gives COP sway as well as biomechanical data about body and joint positions. The ground reaction force data gives 'time to stabilization' of body sway which quantifies dynamic postural stabilization (Fransz et al., 2015). The use of an accelerometer to measure acceleration or deceleration of the COM during movements was theorized to be able to discern dynamic postural stability among more difficult functional movements such as landing and turning (Heebner et al., 2015). It was thought that an accelerometer would better measure postural

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stability because it measured change in motion at the body's COM rather than at the ground-foot level that the force plate measures. Another desirable attribute of the accelerometer is its portability, allowing collection of data outside of the research laboratory setting, possibly at the playing field. However, psychometric investigation of retest reliability and correlations with accepted methods of measuring dynamic stability did not support its use in isolation (Heebner et al., 2015). Current state of the art motion analysis incorporates force plate, accelerometery and videography to measure postural stability. This equipment is expensive and requires significant data analysis expertise to find meaningful information. Additionally, most measurement equipment is not portable (Emery, 2003; Heebner et al., 2015). This has led to the development of clinic and field based measures of sport specific activities such as timed shuttle run, hop for distance and vertical jump measures as a means to measure dynamic postural stability.

Y-Balance Test of Dynamic Postural Stability

One functional performance system that has gained popularity for measuring sport postures and motion is the Functional Movement System (FMS). The FMS consists of a battery of seven movements such as a squat, hurdle stop and inline lunge that are graded for quality of movement. However, a meta-analysis conducted in 2017 found the FMS to be of limited value and recommended against its use for soccer, running, basketball and American football (Moran et al., 2017). A critical review conducted in 2021 had a similar recommendation against using the FMS in high school and professional athletes (Pollen et al., 2021). One of the early components of the FMS was the Star Excursion Balance Test (SEBT). The SEBT test measures how well a person can stand on one leg and move the free leg while maintaining the standing balance. Neuromuscular control is needed while the free leg moves in 8 directions during the test. In studies of the SEBT with athletes, factor analysis found redundancy in using 8 directions

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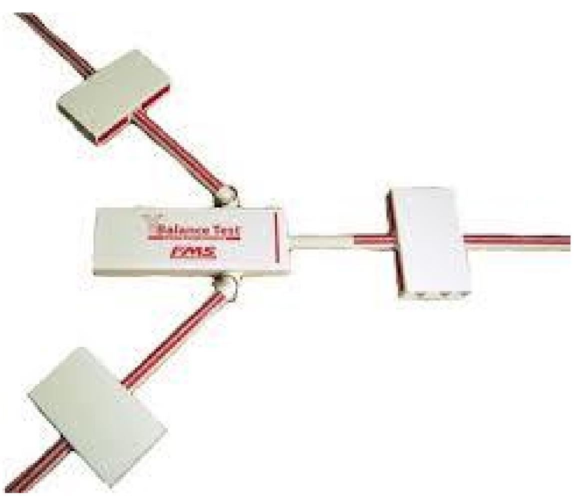
and identified that only 3 of the free leg reach movements were needed to identify unilateral stance differences in injured athletes (Coughlan et al., 2012; Fullam et al., 2013; Hertel et al., 2006; Jagger et al., 2020). The 3 reach directions, anterior, posteromedial and posterolateral have been incorporated into the Y-Balance Test (YBT). To standardize the YBT test procedures, a portable tool that is easy to set up and use was developed. The tool consists of a platform to stand on with 3 removable rods emerging from the platform. The athlete pushes an indicator box along the rod using the foot of the free leg to push the box. The rods have ruler marks every centimeter where maximum reach distances (the distance the indicator box is pushed) are measured. The YBT device is shown in figure 1. The portable YBT tool can measure unilateral dynamic postural stability at the playing field by both researchers and school sport personnel. The value of the YBT is that it measures dynamic neuromuscular control at the limits of postural stability when the athlete has pushed the indicator box as far as possible without losing balance.

Figure 1. Professional Y-Balance Test Device



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When the YBT tool is used to measure postural stability while in unilateral leg stance, the procedure is called the YBT-Lower Quarter (LQ). Over the last decade, the YBT-LQ was used to investigate:

1) screening of athletes (Dingenen et al., 2016; Gonell et al., 2015; Kramer et al., 2019; Šiupšinskas et al., 2019)

2) effectiveness of interventions (Anguish & Sandrey, 2018; Bulow et al., 2021; D'souza et al., 2022; Filipa et al., 2010) and

3) differences in postural ability among sports (Brumitt et al., 2019; González-Fernández et al., 2022; Krysak et al., 2019).

In a recent systematic review with meta-analysis, the YBT-LQ was found to have excellent intra-rater reliability (0.85-0.91) based on 9 reliability studies (P. Plisky et al., 2021). The review article's meta-analysis found differences in YBT-LQ measured postural stability based on age, gender and sport differences including level and type of sport played. The authors conclude that there is a need for more research of dynamic postural stability using the YBT-LQ to establish large data sets of normative data for these categories of differences. There are recent additions to the growing body of knowledge providing reference values for healthy, cleared to play and injured high school athletes. (Bulow et al., 2021; González-Fernández et al., 2022; Jagger et al., 2020; Kramer et al., 2019; Lisman et al., 2018; Onate et al., 2018; P. Plisky et al., 2021; Schwiertz et al., 2020). Despite the addition of the data provided by these studies, the sample size remains low.

The ability of the YBT-LQ to predict musculoskeletal injury in athletes seems to depend on whether individual leg reach distances or asymmetry in reach between legs is considered. A

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2021 systematic review found individual LBT-LQ reach directions and composite scores to not be associated with future injury in 12 of 13 studies (P. Plisky et al., 2021). The authors theorize the finding of non-association may be because studies in the review utilized heterogenous groups of athletes but it is known that performance on the YBT-LQ is unique to age, gender and sport specific participation (Gribble et al., 2012; P. Plisky et al., 2021; Ryu et al., 2019). In prediction studies where a homogenous athlete group was studied with the YBT-LQ, there is evidence of its ability to predict injury. One study calculated an odds ratio of 3.5 (95%CI 2.4-5.3) using a cutoff of 89.6% of leg length (SN=100%, SP=71.7%) to predict injury in collegiate American football players (Butler et al., 2013). Another study not included in the systematic review found a 48% greater risk of suffering an ankle sprain within one year when measuring postural stability in college age regular exercisers if the YBT-LQ posterolateral reach distance was under 80% of leg length (de Noronha et al., 2013). An older study of adolescent female basketball players identified that a composite reach distance of less than 94% of leg length placed an athlete at 6.5 times more likely to sustain a lower extremity injury (P. J. Plisky et al., 2006).

When considering asymmetry between legs as a predictor of injury, the same 2021 systematic review reported 4 of 6 studies in their review supported asymmetry as an injury predictor (P. Plisky et al., 2021). One finding was asymmetry >4 cm in the anterior reach direction predicted injury in collegiate athletes from multiple sports (odds ratio, 2.33; 95% CI 1.15–4.76 and sensitivity, 59%; specificity, 72% (C. A. Smith et al., 2015). This is consistent with an earlier study of high school basketball players also finding a > 4cm asymmetry in anterior reach to be predictive of injury (P. J. Plisky et al., 2006). Another study of male cross country runners found those with > 4 cm difference between legs in the posteromedial direction were 5 times more likely to sustain a running related injury (AOR=5.05, 95% CI: 1.3-19.8;

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p=0.02) (Ruffe et al., 2019). Similarly, asymmetry of > 4 cm in the posteriomedial direction was found to be predictive of injury in collegiate soccer players with a calculated odds ratio of 3.86 (95% CI: 1.46 – 10.95) (Gonell et al., 2015).

In addition to using homogenous athlete groups or asymmetry rather than individual reach distances, some studies are finding better injury risk identification when performance on the YBT-LQ is used in conjunction with other demographic or functional performance data (Hartley et al., 2018; Lai et al., 2017; Lehr et al., 2013; Stiffler et al., 2017). One study identified BMI and YBT-LQ performance as important to consider when screening collegiate male athletes for injury risk (Hartley et al., 2018). In addition to BMI and YBT-LQ performance, sex, prior leg surgery and sport type have been found important for identifying collegiate athletes for risk of injury (Lai et al., 2017). Lehr et al., 2013 developed an algorithm that was able to classify collegiate athletes into a high injury category. Their algorithm includes YBT-LQ and FMS performance, pain during performance and previous injury status. Another study reports receiver operating characteristic (ROC) curves show accurate prediction of musculoskeletal injury when sport type, sex, athletic exposure and anterior reach asymmetry on the YBT-LQ are considered (Stiffler et al., 2017). The use of multifactorial screening that includes the YBT-LQ seems to allow better informed injury identification for collegiate athletes. No studies were found that investigated multifactorial screening in adolescent athletes.

There is a beginning of investigation into the causes of adolescent sport injury when measured using the YBT-LQ. Of particular interest is the effect of fatigue on postural stability. Dynamic postural stability as stated prior requires the integration of the sensory and motor systems. Accurate motor unit recruitment, timing and endurance are needed to produce high load sport performance often at the extremes of joint and muscle tissue tolerance. In a fatigued

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state, injurious compensatory postures and movements can result if the sensorimotor system cannot control the high loads.

Fatigued Sport Performance

It has been noted that most sports injuries occur in the latter parts of sport competition justifying the hypothesis that neuromusculear fatigue plays a significant role (Dvorak, J et al., 2011; Ekstrand, J et al., 2011). A recent systematic review updating knowledge about the effects of neuromuscular fatigue on dynamic postural stability found only 3 articles focused toward fatigue in high school age athletes (Abdelkader et al., 2021). All three articles indicated fatigue did not affect dynamic postural stability in athletes as measured by YBT-LQ. Baghbaninaghadehi et al (2013) studied 15 female basketball players comparing pre-fatigue YBT-LQ performance to fatigued performance and found no difference in dynamic postural stability (Baghbaninaghadehi et al., 2013). Baghbaninaghadehi et.al (2016) compared 15 female handball and basketball athletes to 15 non-athletes and found that while the non-athletes had reduced postural stability after fatigue, the athletes did not (Baghbaninaghadehi et al., 2016). Zech et al (2012) studied 19 male healthy handball players and found no effect of fatigue on dynamic postural stability. The first 2 studies utilized a 20 minute whole body fatigue protocol of warm up jogging, sprinting, push-ups, sit-ups and step up, sprinting again and ended with a fast run. The Borg Rating of Perceived Exertion 6-20 was used to grade fatigue. All athletes had a score of 15 on the RPE when tested with the YBT-LQ. The study by Zech et al. induced whole body fatigue with treadmill running or localized leg fatigue with a step up and heel raise while carrying a barbell for 23-30 repetitions. The Borg Rating of Perceived exertion 6-20 was used to

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grade fatigue. Borg RPE in that study ranged from 15-19 at testing. Neither the whole body nor the local fatigue protocol resulted in reduced YBT-LQ reach performance.

It seems suspect that dynamic postural stability did not suffer a reduction in fatigued state given that we know reduced muscle force correlates with reduced dynamic postural stability, and muscle force production reduces with fatigue. In a study of youth athletes, lower isometric muscle force production highly correlated with reduced dynamic stability measured with the YBT-LQ (Chtara et al., 2018). This was especially true for hip and knee extensors, knee flexors and all planes of ankle muscles except inverters. The authors of that study integrated their isometric strength results with literature about EMG findings during YBT-LQ and found strong agreement. Both their isometric strength and prior reported EMG activity finds the hip extensors are a focus of need for posterolateral YBT-LQ direction stability. The knee extensors are strongly needed for all 3 reach YBT-LQ directions but most importantly for anterior reach. For the ankle muscles, isometric strength and EMG activity in the plantarflexors correlate with both anterior and posterolateral reaches and the dorsiflexors with posteromedial reach. Other studies have also identified a relationship between muscle strength and postural stability, some measuring postural dynamic stability with the YBT-LQ and some with a force plate methodology (Anguish & Sandrey, 2018; Endo & Miura, 2021; Freke & Kemp, 2018; Guirelli et al., 2021; Kaur et al., 2022; M. Santos & Liu, 2008; Wilson et al., 2018). All of these studies identified reduced muscle output resulted in reduced postural stability. Thus, it is fairly well established that reduced muscle force production is associated with reduced dynamic postural stability. The relationship between reduced dynamic postural stability and injury in athletes of all ages and skill level also seems well established (see prior section titled postural stability). The relationship between fatigue and postural stability however is less consistent.

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Neuromuscular fatigue occurs when sport activity requires sustained or repeated muscle activity. Alba-Jimenez et al. (2022) summarized neuromuscular fatigue processes (Alba-Jiménez et al., 2022). Short-term fatigue is believed to occur due to alterations at the neuromuscular junction or metabolically within the muscle itself. Later fatigue occurs due to central nervous system involvement and is thought to be a safeguard mechanism to protect from tissue damage. A summary of the literature about neuromuscular fatigue in adolescents reports sensorimotor functions needed for motor performance are still developing in adolescents (Quatman-Yates et al., 2012). For example, adolescents depend on visual cues more than adults for dynamic postural stabilization. Their joint position sense is well developed but kinesthetic sense is more slowly processed than adults. The vestibular system in adolescents is identified as the slowest sensory process to mature. Quatman-Yates et al. (2012) describe a shift in motion control from jerky ballistic motions in childhood that mature throughout adolescents into smooth motions needed for accurate motor performance and postural control. When fatigue of muscle occurs, the adolescent athlete must depend more heavily on these not fully developed other senses to maintain dynamic postural control.

As noted prior in the systematic review by Abdelkader et al., only 3 studies were found that investigated neuromuscular fatigue effects on dynamic postural stability in adolescent athletes, and no relationship was identified. The sample size in those 3 studies was small, 15 – 19 each, perhaps not allowing enough power to find a difference. The results of those studies are certainly in contrast to other literature that found a negative impact of fatigue on postural stability in other age and ability level athletes. Studies have found post-fatigue reduced postural stability in healthy young adults who are recreationally active (Benjaminse et al., 2008; Reimer & Wikstrom, 2010). This reduced postural stability has also been noted in young adult athletes

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(Chappell et al., 2005; Johnston et al., 2018; Pau et al., 2014, 2016) and young adult athletes with prior injury (Gribble et al., 2004; Hosseinimehr, 2010; Lacey & Donne, 2019; Pfeifer et al., 2018). This finding is also consistent in professional athletes (Bourara et al., 2022; Cárdenas-Montemayor et al., 2014). While this body of literature reports fatigue effects, there are studies showing no fatigue effect on dynamic postural stability (Lacey & Donne, 2019) and some that found fatigue to affect females and males differently with females showing resistance or better tolerance to fatigue than males (Paillard, 2012; Pfeifer et al., 2018; Whyte et al., 2015).

A review article looking at whole body and local fatigue effect on dynamic postural control states reduced postural control occurs when at least 25-30% of pre-fatigue strength is lost (Paillard, 2012). Perhaps the fatigue protocols in the 3 studies in the systematic review of high school age athletes didn't reach this level of reduced muscle output. While the percent reduction in strength was not measured in those 3 studies, they did use the criteria of Borg RPE of 15 or higher which has been used in other studies of fatigue where postural control was found to be compromised. It is possible that the specific muscles used for a sport activity were not fatigued enough to cause a reduced dynamic postural stability. Athletes participating in a specific competitive sport would have a training effect for the specific muscles used for their sport maneuvers. It is recommended that fatigue protocols be sport specific to resolve the discrepancy in findings about the relationship between neuromuscular fatigue and dynamic postural stability (Alba-Jiménez et al., 2022; Paillard, 2012).

Summary

This literature review summarizes what is known and still needing to be known about youth competitive sport participation and injury. Studies of normative data for dynamic postural stability that are age and sport specific are needed to allow the YBT-LQ to be used as a screening

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tool for decisions about readiness or return to play after injury. Larger sample sized studies investigating the effect of fatigue on dynamic balance in youth athletes are needed to inform the body of knowledge about this relationship in youth athletes as compared to what is known in adult athletes. The studies need to include both male and female youth athletes. Additionally, the fatigue inducing protocols need to be sport specific. This information could inform injury prevention programs so that they tailor training activities to the age, sport participation and gender of the team athletes. This dissertation study kept these needs in mind during the development of its methodology.

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Chapter Three

Methodology

The primary purpose of this study was to investigate the effect of neuromuscular fatigue induced by sport specific activities on dynamic postural stability in the youth athlete population. The secondary purpose was to provide both fatigued and non-fatigued postural stability data that can be used to reference typical performance (normative data) of both male and female youth athletes participating in common high school sports. The methodology for the study used a non-random pre-post design. The independent variable was sport specific induced fatigue and the dependent variable was SLS postural stability measured with the YBT-LQ device.

Research Question

In addition to providing normative data, this research was designed to answer three questions:

1. Is there an effect of fatigue on the ability of youth athletes to maintain postural stability during dynamic SLS?
2. Does fatigue challenge the postural stability of male and female athletes equally?
3. Do youth athletes playing a specific sport experience fatigued SLS postural stability differently than youth athletes from other sports?

Target Population and Sampling

The population of interest for this study is high school athletes playing competitive sports for their school. Convenience sampling of athletes occurred from high schools local to the Youngstown, Ohio area, playing in one of these sports teams: basketball, baseball/softball, soccer, track, and lacrosse.

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Inclusion Criteria

- Attending grades 9-12
- Non-injured or completely cleared (by the treating physician) to play sport the day of testing
- Able to perform acceptable reach trials using the YBT-LQ testing- the detailed criteria defining an acceptable reach trial is provided in a subsequent section titled "Pre-fatigue Testing".

Exclusion Criteria

- Unable to understand the assent/consent material explaining the risks and benefits of the research
- Current injury in any body area including concussion.

Research Procedures

Preparation: Human subjects protection approval was obtained from the Youngstown State University Institutional Review Board. Coaches at local high schools were given written information describing the research project. Appendix A provides the information to coaches. If a coach was interested, I obtained a letter of support from the school's athletic director and school superintendent. Recruitment of student athletes then occurred throughout the school year, at the beginning of the sport's playing season. At an early season team practice, I introduced the athletes to the purpose and procedures of the project and provided assent/consent and demographic forms. The demographic form is shown in Appendix B. After receiving the documents back, eligibility to participate was identified based on inclusion & exclusion criteria. A data collection date was scheduled with the coach at a future practice session for the athletes able to participate. Athletes were instructed to avoid greater than mild activity for 5 hours prior

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to this practice session. Since practices were scheduled right after school, this requirement was not burdensome.

Research activity: Prior to the scheduled team practice, I set up the YBT-LQ device near the practice field. For basketball this was at the sideline of the court or in the hallway outside the court. For baseball/softball, soccer and lacrosse a field equipment building with a smooth and level cement floor was available for set up. For track, the only area near the athletes practicing was a cemented sidewalk like surface area. The YBT-LQ device was moved several times until the surface was level enough to allow smooth movement of the measuring block along the yardstick rod.

When athletes began to arrive for practice, they first came to the testing area to confirm demographic information, have leg length measured, and to practice testing procedures. The structural leg length measurement recommended by the YBT-LQ manufacturer's manual is from the most distal surface of the anterior superior iliac spine (ASIS) to the most inferior aspect of the medial malleolus, measured in centimeters to the nearest .05 cm without shoes. The leg length measured for this study varied in 2 ways. First, the device's instruction manual guides that (structural) leg length be measured in the supine position. Because the testing was not done in a laboratory setting there was not a suitable surface for the athlete to lie down. Additionally, athletic injuries occur when athletes are weight bearing so even though standing introduces functional limb length considerations, it is reasonable to use standing leg-length measures. Therefore, leg length was measured with the athlete standing and special care taken to ensure equal weight bearing and upright body stance while on a level surface. The second variance from the measurement guideline was that distance was measured from the ASIS to the floor on the medial side of the foot at the level of the medial malleolus. This leg length was taken to

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accommodate the athlete wearing shoes during testing. Studies comparing dominant to non-dominant leg single leg postural stability, including some using the BT-LQ have not found a difference in reach distances based on leg dominance (Bressel et al., 2007; Emery, 2003; Huurnink et al., 2014; Sabin et al., 2010; Stoddard et al., n.d.; Thorpe & Ebersole, 2008) . Studies of leg length inequality have found the difference to be less than 1.1 cm in 70 -96% of typically developed skeletally mature adults (Aitken, 2021; Brady et al., 2003; Hellsing, 1988; Vogt et al., 2020). In a study of high school runners with a leg length asymmetry, the difference was .42 cm (Rauh, 2018). A cadaveric study found 90% of the specimens had a difference of only 1 cm with the average difference being 4 mm (Liu et al., 2018). Information available on the website of the Children's Hospital of Philadelphia reports leg length inequality is 1cm or less in typically developing children (Philadelphia, 2017). Given the evidence of no effect of leg dominance and the assumption of little leg length difference for an individual athlete, only the right leg length was measured to keep the athlete time away from practice as short as possible.

Instrument and Procedure

Postural stability was measured with the YBT-LQ protocol. The YBT-LQ kit requires the user to assemble 3 cylindrical wood bars into a rectangular block with one bar pointing anterior, one posteromedial and one posterolateral to the block. Figure 1 shows the YBT-LQ device set up. The bars have 0.5 cm marks on them for measuring how far the athlete reaches. There is a moveable indicator block that slides when the athlete pushes it along the bar without weight bearing on the block. The YBT-LQ device must be placed on a flat surface so that the surface does not interfere with sliding of the indicator block.

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Pre-fatigue testing

Each athlete was instructed in the testing procedure including common errors during testing. The single limb standing posture and contralateral leg reaching maneuvers were demonstrated. Acceptable reach performance and reach deviations that would negate a reach trial were also demonstrated. Each athlete then practiced proper procedure for maneuvering the indicator block in the 3 reach directions with each leg. Prior literature used 3-6 reach trials per reach direction per leg in their methodology (González-Fernández et al., 2022; Jagger et al., 2020; P. J. Plisky et al., 2009; Shaffer et al., 2013). Each athlete in this study performed at least 3 trials and more if time allowed or if the athlete was struggling to complete ‘acceptable’ reaches.

After practicing on the YBT-LQ device, each athlete rested before being tested for pre-fatigue postural stability. During testing, the athlete stood upright on one leg on the rectangular block, with the front edge of the shoe in alignment with a mark near the anterior tip of the box. While maintaining single leg stance, the athlete reached with the contralateral leg and pushed the indicator box along the bar. The athlete performed reaches on all 3 of the bars in this sequence: Right leg anterior direction, left leg anterior direction, right leg posteromedial, left leg posteromedial, right leg posterolateral, left leg posterolateral. Criteria for a reach to be documented as a successful trial required the athlete to move the indicator box without weight bearing on it and without losing contact with the box. The reaching leg also had to return to the upright SLS position without touching the ground or the bar on the return. The athlete’s arms were free to move and the weight bearing heel was allowed to raise. This criteria adheres to the manufacture’s guidelines and procedures used by the previously referenced researchers using the YBT-LQ in their studies (González-Fernández et al., 2022). Reach trials were continued until

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three successful reaches in all 3 directions were completed for each leg. To identify the reach distance, the researcher noted the bar's measurement mark closest to the trailing edge of the indicator box at the end of the reach maneuver. The on-site data collection sheet is provided in Appendix C.

Fatigue Protocol

After pre-fatigue testing, each athlete was educated in the Borg Rating of Perceived Exertion (RPE) so that it could be used to determine timing of post –fatigue postural stability testing (*Perceived Exertion (Borg Rating of Perceived Exertion Scale) | Physical Activity | CDC*, 2022) Appendix D contains the Borg RPE. A written copy of the 6-20 point scale with the level of exertion corresponding to a point on the scale was provided to each athlete. The researcher instructed that the target level on the Borg RPE for post-fatigue testing was at least hard to very hard (RPE interval on the Borg RPE document of 14-15 or greater points. Each athlete was instructed that post fatigue testing needed to occur within 4 minutes of leaving the practice field. Once the athlete verbalized understanding of the needed level of fatigue and 4 minute requirement, the athlete joined the coach and remainder of the team to participate in coach specified sport training activities.

In discussion with each coach at the initial recruitment session, the coach was instructed that the practice session should be typical for preparing athletes for the sport season. The only research requirement told to the coach was that the athletes needed to be able to attain an RPE of at least 14-15 interval of points during the practice session.

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Post -fatigue testing

The athletes returned for testing one at a time when they reached the RPE requirement and received coach permission to leave practice for testing. The athlete was immediately shown the Borg RPE document and asked to identify current RPE. If RPE was not adequate, the athlete returned to the practice session with renewed Borg RPE instructions. Those who met the target RPE were immediately tested using the same procedure with the YBT-LQ as pre-fatigue. All were tested for post-fatigue postural stability within a 4 minute time requirement. This is well within the 10 minute time that dynamic stability recovers from fatigue when specifically measured with the YBT-LQ (Johnston et al., 2018) .

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Chapter Four

Sample Description**.**

The sample population consisted of both male and female athletes in 9th – 12th grade attending one of 7 schools in northeast Ohio. The number of athletes initially recruited was 260. However, 3 could not be tested due to missing parental consent, 2 were not yet released to play after a recent injury, and 2 had missing data for leg length. Single leg reach distances cannot be normalized without leg length and therefore those athletes' data were not able to be used. The final number of participant data available for statistical analysis was 253.

Data Inspection

Data transfer accuracy: Data recorded on a paper collection sheet at the time of testing at each school was manually transferred to an excel spreadsheet. Errors in data entry are known to widen confidence intervals with the implication of incorrect statistical conclusions (Kozak et al., 2015). An audit of 10 percent of the total data entries was checked for accuracy using the partner read aloud process. An 0.08% error rate (2 of 25 entries) was identified which is lower than the typical range of 0.55-3.6% for manually entered research data (Barchard et al., 2020). Nonetheless, another 10% of the data were checked with no further data transfer error noted.

Missing data: As noted above, there were 2 incidents of missing leg length so none of the data for those 2 participants could be used resulting in 253 final participant data. There was only one athlete for whom a pre-fatigue reach direction was completely missing any data and that was for the posteromedial direction. During testing, this athlete could not perform this reach direction without violating criteria for an acceptable test even after 10 attempts. Four athletes did not return for post-fatigue data collection. This occurred when 2 athletes needed to leave early from practice due to personal schedule and twice when a coach needed continuous presence

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of the athlete to the practice session. These reasons indicate the missing data was completely at random (not influenced by other data) which allows imputation if needed to maintain sample size (Austin et al., 2021; Tan et al., 2021). The sample size for the planned statistical analysis was 128 (64 per group) for a power of .80 and a medium effect size. Therefore, it was determined that imputation for missing data was not indicated.

Demographics

Descriptive information for age, rate of perceived exertion and sex is shown in table 1. The number of athletes participating in each sport is provided in table 2.

Table 1. Participant Demographics

	Mean	S.D.
Age (yrs)	16.1	1.2
RPE*	14.8	1.31
	Frequency	Percent
Female	100	39.5
Male	153	60.5
Total	253	100.0
*RPE = Borg's Rate of Perceived Exertion		

Table 2. Sport Participation

	Female	Male	Total
Basketball	39	56	95
Baseball	0	38	38
Softball	30	0	30
Lacrosse	17	9	26
Soccer	0	33	33
Track	12	14	26

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Normative data

Each participant's absolute and normalized reach distance for the 3 reach directions were calculated for each leg and normalized by his/her leg length using these formulas:

- Absolute reach distance (cm) = (Reach 1 + Reach 2 + Reach 3) / 3
- Relative (normalized) reach distance (%) = Absolute reach distance / limb length * 100

The following formula combined the 3 reach directions into a composite value for each leg of each athlete: Composite reach distance (%) = Sum of the 3 reach directions / 3 times the limb length * 100.

Once each athlete's normalized reach distances and composite scores were calculated, the group mean for the sample was calculated for each reach distance and composite score both at pre-fatigue testing (baseline) and after fatigue. Normative data of the sample means and confidence intervals for the 3 reach directions and the composite value for each leg are shown in the tables below. The table 3 shows pre-fatigue norms for female participants and table 4 shows pre-fatigue norms for male participants.

Table 3. Female Athlete Normalized Reach Distance Pre-fatigue

Right Leg						Left Leg				
Reach Direction			Distance (cm)	Std. Error		Reach Direction			Distance (cm)	Std. Error
Pre-Anterior	Mean		62.72	0.65		Pre-Anterior	Mean		62.63	0.59
	95% CI	Lower	61.43				95% CI	Lower	61.46	
		Upper	64.01					Upper	63.79	
	Min		48.52				Min		51.02	
	Max		85.77				Max		82.61	
Pre-PM*	Mean		91.71	1.12		Pre-PM*	Mean		92.79	1.05
	95% CI	Lower	89.49				95% CI	Lower	90.70	
		Upper	93.93					Upper	94.88	
	Min		67.33				Min		64.85	
	Max		118.47				Max		114.39	
Pre-PL**	Mean		92.05	0.98		Pre-PL**	Mean		91.67	0.89
	95% CI	Lower	90.09				95% CI	Lower	89.90	
		Upper	94.00					Upper	93.43	
	Min		70.18				Min		64.77	
	Max		111.93				Max		114.75	
Pre-Composite	Mean		82.16	0.79		Pre-Composite	Mean		82.37	0.72
	95% CI	Lower	80.59				95% CI	Lower	80.94	
		Upper	83.73					Upper	83.80	
	Min		65.35				Min		63.53	
	Max		100.50				Max		98.83	

*PM = posteromedial direction **PL = posterolateral direction

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Table 4 Male Athlete Normalized Reach Distance Pre-fatigue

Right Leg					**Left leg**				
Reach direction			Distance (cm)	Std. Error	Reach direction			Distance (cm)	Std. Error
Pre-Anterior	Mean		62.74	0.58	Pre-Anterior	Mean		63.17	0.59
	95% CI	Lower	61.6			95% CI	Lower	62.01	
		Upper	63.88				Upper	64.33	
	Minimum		40.1			Minimum		39.11	
	Maximum		79.78			Maximum		82.05	
Pre-PM*	Mean		90.72	0.95	Pre-PM*	Mean		92.52	0.92
	95% CI	Lower	88.84			95% CI	Lower	90.7	
		Upper	92.6				Upper	94.33	
	Minimum		47.55			Minimum		57.52	
	Maximum		119.16			Maximum		124.14	
Pre-PL**	Mean		92.43	0.75	Pre-PL**	Mean		92.49	0.81
	95% CI	Lower	90.96			95% CI	Lower	90.88	
		Upper	93.91				Upper	94.1	
	Minimum		68.27			Minimum		68.97	
	Maximum		128.46			Maximum		122.1	
Pre-Composite	Mean		81.96	0.64	Pre-Composite	Mean		82.82	0.64
	95% CI	Lower	80.71			95% CI	Lower	81.55	
		Upper	83.22				Upper	84.1	
	Minimum		59.24			Minimum		58.51	
	Maximum		107.49			Maximum		108.68	

*PM = posteromedial direction **PL = Posterolateral direction

Parametric Statistic Assumption Analysis

The planned *t*-tests and one way ANOVA statistics are considered to be robust to violation of the assumptions of parametric statistics (Hopkins, K & Weeks, D, 1990). None-the-less, evaluation for normality and equal variance was conducted for each variable. SPSS v. 28.0.1.1 was used for both assumption analysis and statistical analysis for hypothesis testing.

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The assumption of normal distribution was checked using visual observation of boxplots for outliers and calculations of skewness (symmetry) and kurtosis (thick or thin tailedness). Observation of the boxplots showed the reach direction of left leg anterior pre-fatigue to be in a non-normal distribution. The entered data were checked against the hard copy data collection sheet and the data for the anterior and posteromedial reach directions were transposed for one individual. There was a note on the data collection sheet at time of entry of data that this transposition had occurred but missed during data entry. The transposition resulted in a significantly skewed distribution for the anterior direction but not for the other reach directions for the left leg pre-fatigue. This is because the transposed values were within quartile 1 and quartile 3 for both the posteromedial and posterolateral reaches but not for anterior reach. After the transposition was corrected, the boxplot was rerun and showed normality of distribution.

For the pre-fatigue reach directions and composite variables, skewness ranged from -.102 to .304 and for post fatigue skewness ranged from -.017 to -.173, where negative values indicate a longer left tailed distribution and positive values indicate a longer right tailed distribution. The acceptable level of skewness to meet the criteria of normality is values between -2 and +2 (Cain et al., 2017; Kim, 2013). Kurtosis ranged from -.066 to .813 for pre-fatigue variables and -.34 to .957 for post fatigued. Acceptable kurtosis values are between -3 and +3 for SPSS calculated kurtosis (Hopkins, K & Weeks, D, 1990; Watson, 2021). The Levene Test for testing the assumption of equal variance showed no significant findings at the alpha = 0.05 level. The nearest Levene test p-value to being significant was 0.108 indicating the assumption of homoscedasticity was met.

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Hypothesis Testing

Hypothesis 1: There will be no difference between pre-fatigue and fatigued reach distances for all 3 reach directions and composite scores. This hypothesis will determine if there is an effect of fatigue on SLS composite reach performance. For each participant, a difference score was calculated from the pre fatigue to post fatigue scores using the formula: pre-fatigue composite score – post fatigue composite score = difference composite score. A positive score indicates post fatigue had a reduced SLS composite while a negative score indicates post fatigue SLS composite scores were greater than pre fatigue. Hypothesis 1 was tested using a non-directional paired *t*-test rather than a directional analysis due to the discrepancy in the literature about whether fatigue reduces reach distances or not for different athletic populations. The paired *t*-test comparing mean difference composite scores was conducted with alpha set to 0.05.

The analysis for comparing composite scores found a significant difference for left SLS composite but not the right SLS composite. The mean difference was 0.546 cm (CI: 0.015 – 1.07) with pre fatigue composite larger than post fatigue. The Cohen's *d* for the effect size of fatigue on left SLS composite is .129 (CI .004-.253).

To further test this hypothesis, the 3 reach directions for each leg were also compared for the effect of fatigue. The difference scores for each participant's reach direction for each leg were calculated similarly to the composite score using: pre fatigue reach distance – post fatigue reach distance = reach difference. Again, a positive value indicates the post fatigue distance was reduced and a negative value indicates fatigued distances were greater than non-fatigue. Paired *t*-tests were run using the mean difference for each reach direction using a non-directional paired *t*-test with alpha = 0.05.

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Table 5 provides results of the statistical inquiry with the Cohen *d* effect size provided for significant findings. Only the anterior reach distance for both the right and left legs was found to be statistically different, and in the direction of reduced distance when fatigued. The effect size of this difference is small. When observing the group means for non-significant reach directions, the posterolateral reach distance for both legs increased after fatigue. The reach change was variable for the posteromedial direction with the RLE showing greater reach distance with fatigue but the opposite for the LLE.

Table 5 Difference in Reach Distance from Pre to Fatigued Status

Paired Samples T-Test									
	Reach Direction Difference	Mean Diff (cm)	SD	95% CI	t	df	2-Sided p value	Cohen d	95% CI Cohen d
RLE	Pre-Anterior to Fatigued Anterior	1.3	5.06	.67-1.94	4.06	247	<.001*	0.26	.13-.38
	Pre-PM to Fatigued PM	-0.7	6.8	-1.7	-1.63	247	0.1		
	Pre-PL to Fatigued PL	-0.15	6.36	-1.59	-0.37	247	0.72		
LLE	Pre-Anterior to Fatigued Anterior	1.55	4.45	.99-2.10	5.48	247	<.001*	0.35	.22-.48
	Pre-PM to Fatigued PM	0.7	6.43	-1.61	1.72	246	0.09		
	Pre-PL to Fatigued PL	-0.63	5.77	-1.44	-1.73	247	0.09		

RLE = right leg, LLE = left leg. Mean Diff = difference in reach distance from pre to fatigued status measured in centimeters (cm).
PM = posteromedial direction. PL = posterolateral direction. * at alpha = .05

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Hypothesis 2: Female participants will have less fatigue effect on postural stability than the males. This hypothesis will determine if gender plays a role in fatigued SLS reach performance. To test this, the mean difference scores (pre fatigue – post fatigue = difference score) were calculated and the data set was divided into male and female groups. Hypothesis 2 was tested with a directional independent *t*-test comparing the 2 groups due to evidence in the recent literature that SLS performance of female athletes showed stability while male reach distances declined (Paillard, 2012; Pfeifer et al., 2018; Whyte et al., 2015). Independent *t*-tests compared mean differences between females and males with alpha set to 0.05.

The independent t-test results showed no significant statistical results for any reach direction or composite for either leg. These results do not support the hypothesis of less fatigue effect on performance by female athletes compared to males. Looking closer at the data, the mean difference scores for the females were larger than the males for 6 of the 9 reach variables. While this pattern between the genders was small in magnitude, it seemed to indicate the males did better in fatigued SLS postural control than females. However, given the original directional t-test, this conclusion cannot be made (Lakens, 2016). Therefore, the results of non-directional independent t-tests for each reach direction were also considered. This non-directional testing found no significant difference between males and females in fatigue induced reach performance.

Hypothesis 3: There will be no differences in fatigued reach distances based on sport participation. This hypothesis will determine if athletes playing a specific sport will experience fatigued SLS postural stability differently than athletes from other sports. As before, difference scores were calculated and the data set was divided into groups based on sport participation.

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Hypothesis 3 was tested with a one-way ANOVA with sport as the independent variable and SLS reach distances as the dependent variable. For reach variables found significant by the omnibus one-way ANOVA, post hoc analysis was completed using the Tukey HSD test to identify the sport/s contributing to this difference. Female and male athletes were analyzed separately because there are no female soccer players. The sports included were basketball, baseball, softball, soccer, track, and lacrosse. The alpha level was set to 0.05 for the one-way ANOVA tests.

The descriptive values for difference scores for each reach direction grouped by sport which were found significant by the omnibus one-way ANOVA are shown in table 6 for females and table 7 for males.

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Table 6. Female Difference Values for Significant ANOVA Reach Directions

			N	Mean Difference	SD	95% CI	
						Lower Bound	Upper Bound
RLE	Anterior	Basketball	39	1.38	6.05	-0.58	3.34
		Lacrosse	17	4.78	4.89	2.27	7.30
		Softball	30	-0.54	4.95	-2.39	1.30
		Track	12	1.01	4.14	-1.62	3.64
		Total	98	1.33	5.54	0.22	2.45
	Posteromedial	Basketball	39	-1.76	6.28	-3.80	0.28
		Lacrosse	17	4.09	7.10	0.44	7.74
		Softball	30	-2.95	4.96	-4.80	-1.10
		Track	12	-0.84	7.82	-5.81	4.13
		Total	98	-1.00	6.63	-2.33	0.33
	Posterolateral	Basketball	39	-0.93	6.48	-3.03	1.17
		Lacrosse	17	4.41	6.74	0.95	7.88
		Softball	30	-1.99	4.81	-3.79	-0.19
		Track	12	-0.19	9.63	-6.31	5.93
		Total	98	-0.24	6.81	-1.60	1.13
	Composite	Basketball	39	-0.44	4.16	-1.79	0.91
		Lacrosse	17	4.43	5.07	1.82	7.04
		Softball	30	-1.83	3.71	-3.21	-0.45
		Track	12	-0.01	4.91	-3.13	3.11
		Total	98	0.03	4.74	-0.92	0.98
LLE	Posterolateral	Basketball	39	-1.75	5.28	-3.46	-0.04
		Lacrosse	17	3.75	8.22	-0.48	7.98
		Softball	30	-3.30	4.81	-5.09	-1.50
		Track	12	-0.75	6.07	-4.60	3.10
		Total	98	-1.15	6.24	-2.40	0.10
	Composite	Basketball	39	-0.26	3.21	-1.31	0.78
		Lacrosse	17	4.02	6.01	0.93	7.11
		Softball	30	-0.77	3.59	-2.11	0.57
		Track	12	1.33	3.99	-1.20	3.86
		Total	98	0.52	4.32	-0.35	1.39

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Table 7. Male Difference Values for Significant ANOVA Reach Directions

			N	Mean Difference	SD	95% CI	
						Lower Bound	Upper Bound
RLE	Posteromedial	Basketball	56	-0.84	6.55	-2.60	0.91
		Baseball	38	-1.94	5.63	-3.79	-0.09
		Lacrosse	9	3.12	5.32	-0.97	7.21
		Soccer	33	1.72	6.28	-0.50	3.95
		Track	14	-2.92	11.27	-9.43	3.58
		Total	150	-0.51	6.91	-1.63	0.60
	Posterolateral	Basketball	56	1.48	5.92	-0.10	3.07
		Baseball	38	-1.02	5.60	-2.85	0.82
		Lacrosse	9	4.17	8.34	-2.25	10.58
		Soccer	33	-2.13	5.45	-4.06	-0.19
		Track	14	-1.79	5.42	-4.92	1.34
		Total	150	-0.09	6.07	-1.07	0.89
	Composite	Basketball	56	0.53	3.88	-0.50	1.57
		Baseball	38	-0.51	4.10	-1.85	0.84
		Lacrosse	9	4.05	5.58	-0.24	8.34
		Soccer	33	0.35	3.47	-0.88	1.58
		Track	14	-1.76	4.98	-4.64	1.12
		Total	150	0.23	4.19	-0.45	0.90
LLE	Posterolateral	Basketball	56	0.37	5.20	-1.02	1.76
		Baseball	38	-0.48	6.45	-2.60	1.64
		Lacrosse	9	1.02	4.46	-2.41	4.45
		Soccer	33	-0.97	4.72	-2.64	0.70
		Track	14	-1.70	5.63	-4.95	1.55
		Total	150	-0.29	5.43	-1.17	0.58
	Composite	Basketball	56	1.32	4.33	0.16	2.48
		Baseball	38	-0.37	4.45	-1.84	1.09
		Lacrosse	9	2.13	3.41	-0.50	4.75
		Soccer	33	0.59	3.59	-0.69	1.86
		Track	13	-1.10	4.23	-3.65	1.46
		Total	149	0.56	4.20	-0.12	1.24

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This descriptive data shows that lacrosse is the only sport where athletes had reduced reach distances for reach directions when fatigued. This held true for both female and male athletes. Softball and baseball were consistent with each other but showed greater reach distances when fatigued. Males who participated in track showed greater reach distances when fatigued but female track athletes were variable with some reach directions attaining greater and some reduced distances when fatigued. Male soccer athletes (there are no female soccer players) and both female and male basketball players were variable with some reach directions attaining greater and some reduced distances when fatigued. The actual differences in reach distances, whether increased or decreased for each sport are shown in table 8. The minimum value indicates the smallest distance that any reach direction differed and the maximum value indicates the greatest distance that any reach direction differed.

Table 8. Range of Reach Distance Differences by Sport.

	Sport	Response of Reach Distance to Fatigue	Reach Distance in cm	
			Minimum	Maximum
Females	Basketball	Variable across reach directions		
	Lacrosse	Reduced fatigue reach distance	3.79	4.78
	Softball	Increased fatigue reach distance	0.54	3.3
	track	Variable across reach directions		
Males	Basketball	Variable across reach directions		
	Baseball	Increased fatigue reach distance	0.37	1.9
	Lacrosse	Reduced fatigue reach distance	1.02	4.17
	Soccer	Variable across reach directions		
	Track	Increased fatigue reach distance	1.1	2.9

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The one-way ANOVA for the female athletes found significant differences among sports for all 3 reach directions & composite score for the RLE, but for the LLE only the posterolateral reach and composite score were found to have differences among sport.

The one-way ANOVA for male athletes found significant differences among sports for RLE posteromedial and posterolateral reaches and the composite score but not for the anterior reach direction. There were no significant differences among sports for the LLE reaches or composite variables.

Significant results of the omnibus one-way ANOVA for females and males are shown in the below 2 tables with the associated partial eta squared effect size noted. Effect size values are in the medium to large effect categories (Watson, 2021)

The post hoc analysis was able to identify the sports that contributed to a fatigue effect found by the omnibus ANOVA. For female athletes, lacrosse was the only sport that differed from the rest of the sports. None of the other sports differed amongst themselves. The mean difference score for lacrosse was positive for each reach directions indicating a reduced reach distance with fatigue. For male athletes, lacrosse differed from all other sports except basketball. None of the other sports were found to differ amongst themselves. Once again, all the mean difference scores were positive indicating males also had reduced reach distance with fatigue.

Results of the post hoc analysis to identify which sport/s contributed to the ANOVA findings are shown in table 9.

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Table 9. Female Significant Differences Found by Omnibus One-way ANOVA

`	Direction Pre to Fatigued		Sum of Squares	df	Mean Square	F	Sig.	Eta2	Eta2 CI
RLE	Anterior	Between Groups	309.47	3	103.16	3.63	0.02	0.104	.004-.208
		Within Groups	2670.15	94	28.41				
		Total	2979.62	97					
	Posteromedial	Between Groups	578.19	3	192.73	4.91	0.00	0.135	.018-.246
		Within Groups	3691.95	94	39.28				
		Total	4270.15	97					
	Posterolateral	Between Groups	478.41	3	159.47	3.73	0.01	0.106	.005-.211
		Within Groups	4015.20	94	42.72				
		Total	4493.61	97					
	Composite	Between Groups	441.30	3	147.10	7.97	<.001	0.203	.060-.320
		Within Groups	1733.97	94	18.45				
		Total	2175.27	97					
LLE	Posterolateral	Between Groups	562.29	3	187.43	5.48	0.002	0.149	.026-.261
		Within Groups	3216.10	94	34.21				
		Total	3778.38	97					
	Composite	Between Groups	289.80	3	96.60	5.98	<.001	0.16	.032-.274
		Within Groups	1518.46	94	16.15				
		Total	1808.26	97					

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Table 10. Male Significant Differences Found by Omnibus One-way ANOVA

	Direction Pre to Fatigued		Sum of Squares	df	Mean Square	F	Sig.	eta2	Eta2 CI
RLE	Posteromedial	Between Groups	449.07	4	112.27	2.44	0.05	0.06	.000-.129
		Within Groups	6674.71	145	46.03				
		Total	7123.77	149					
	Posterolateral	Between Groups	511.26	4	127.81	3.72	0.01	0.09	.009-.170
		Within Groups	4979.14	145	34.34				
		Total	5490.40	149					
	Composite	Between Groups	213.23	4	53.31	3.21	0.02	0.08	.003-.155
		Within Groups	2405.04	145	16.59				
		Total	2618.27	149					

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Table 11. Fatigue Affect by Sport

Females		**Sport**	**Differs From**
RLE		Basketball	Lacrosse
		Lacrosse	Basketball
			Softball
			Track
		Softball	Lacrosse
LLE		Track	Lacrosse
Males		**Sport**	**Differs From**
RLE		Basketball	None
		Baseball	Lacrosse
		Lacrosse	Track
			Soccer
			Baseball
LLE		Soccer	Lacrosse
		Track	Lacrosse

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Chapter Five

This study investigated the effect of fatigue on postural stability in high school athletes participating in basketball, baseball/softball, lacrosse, soccer or track. Fatigue was induced by sport specific training sessions led by the team coach. Postural stability was measured with the YBT-LQ which requires the athlete to maintain single leg stance while reaching with the non-weight bearing leg in 3 directions. The study tested these 3 hypotheses:

> Hypothesis 1: There will be no difference between pre-fatigue and fatigued reach distances for all three reach directions and composite scores.
>
> Hypothesis 2: Female participants will have less fatigue effect on postural stability than the males.
>
> Hypothesis 3: There will be no differences in fatigued and non-fatigued reach distances based on sport participation

Hypothesis 1 was supported with this study's data except for small statistical differences in pre-fatigue and fatigued reach distances that did not reach clinical significance. Male and female adolescent athletes performed similarly in this study and did not support hypothesis 2. Lacrosse athletes did have reduced reach distance when fatigued but none of the other sports found this relationship indicating partial support of hypothesis 3. In addition to hypothesis testing, another outcome of the study is the creation of normative fatigue data for 253 athletes participating in 6 sports at 7 schools in northeast Ohio

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Normative Data

The typical reach pattern found for healthy young people is for the posteromedial and posterolateral reaches to be similar to each other but the anterior direction to be less in distance to them by 20- 30 cm (Alnahdi et al., 2015; Jagger et al., 2020; Onate et al., 2018; P. J. Plisky et al., 2006; Schwiertz et al., 2020). The normative values in my study also followed this pattern of reach distances. In the just referenced studies, the actual distances for each reach direction were similar among the studies. Unlike the reach distances in those studies, my reach distances are significantly less for each reach direction. For example, Schwiertz et. al. (2020) (Schwiertz et al., 2020) reports anterior reach at the 50^{th} percentile for a healthy 16 yo to be 75.8 cm. Pliskey et, al. (2006) (P. J. Plisky et al., 2006) reports anterior reach to be 84 cm in high school basketball players and Onate et.al. (2018) (Onate et al., 2018) reports anterior reach for high school athletes in general to be 71.6 cm. The value for anterior reach in my study is 62 cm. Initially I theorized this distance discrepancy would be explained by my method of measuring leg length. The athletes in my study wore their typical practice shoes during testing so to control for shoe height, I measured leg length from ASIS to floor below the medial malleolus rather than to the distal malleolus. The formula for normalizing reach distances by leg length is: reach distance/leg length. Having a longer leg length measurement in the denominator would reduce the normalized distance value. When I compared the leg length values for my participants to the leg length reported by other studies with high school athletes my leg length discrepancy was approximately 4 cm (1.58 inch) for males and 6 cm (2.36 in) for females. It seemed reasonable that a combination of distance from malleolus to shoe surface and shoe sole height would be similar to these discrepancy measurements. However, when I re-ran calculations for normalized

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reach distances using a reduced denominator value (removed shoe height) similar to the values above, there was still substantial discrepancy for my reach distances compared to the other studies.

Data collection in my study was conducted in places very near to the practice setting of the sport team and testing surfaces included cement floors both in locker rooms and on sidelines. I examined several of the published studies including those with high school athletes to determine floor surface when testing. None of the studies identified a non-typical floor surface and in articles with pictures of YBT-LQ performance, all surfaces were of smooth material. During piloting of my study, I recognized friction as a possible confounder so routinely used silicone spray on the bottom of the YBT-LQ device. The test floor surface was also sprayed when possible. During testing, the athletes seemed to be able to move the YBT-LQ marker with ease but it is possible that the increased friction of the floor surface contributed to reduced reach distances in my study compared to normative data from other studies.

Postural stability especially in the sagittal plane is affected by shoe wearing (Reutimann et al., 2022). Even soft soled ballet slippers increased SLS center of pressure oscillations compared to barefoot when the lifting leg is moved anteriorly, posteriorly or to the side during ballet dance movements (Lobo da Costa et al., 2013). In a study investigating the effect of different sole thicknesses on ankle proprioceptive sense, the thicker soles reduced dorsiflexion sense more than plantarflexion, inversion or eversion (Sekizawa et al., 2001). All three of the YBT-LQ reach maneuvers require significant dorsiflexion motion (S. Nelson et al., 2021). Therefore, the choice to test athletes in their shoes may have also contributed to the reduced reach distances in my study. The choice to test with typical shoes of the sport was to simulate

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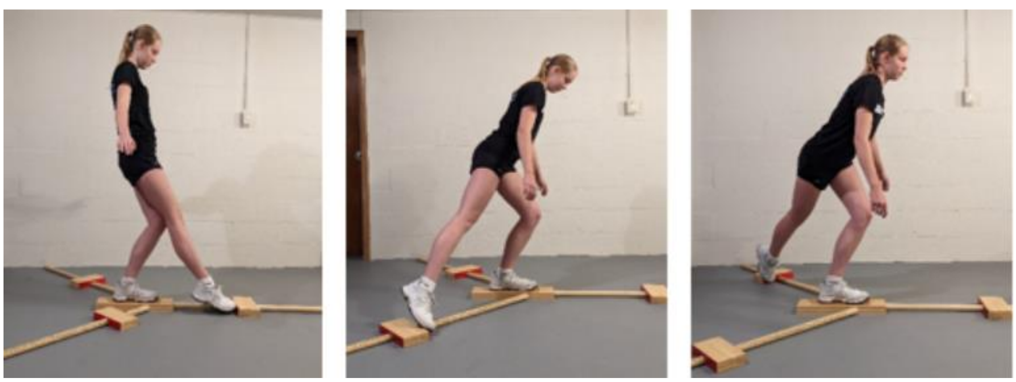
the actual playing situation as much as possible. Shoe wearing during YBT-LQ testing is not without precedent. In an early study finding strong testing reliability of the YBT-LQ to measure postural stability, the methodology included wearing of shoes (P. J. Plisky et al., 2006). Other studies investigating postural stability with the YBT-LQ completed their study with participants wearing athletic shoes (Earl-Boehm & Hertel, 2001; English & Howe, 2007; Hertel et al., 2000; Onate et al., 2018).

Fatigue effect on reach distances

There are few studies investigating the effect of fatigue on postural stability specific to high school age athletes. The systematic review article did include three studies with high school athletes participating in competitive sports (Abdelkader et al., 2021). While that review found small to large effect of fatigue in other age athletes, the high school athletes did not experience significant change in YBT-LQ reach distances. My study supports this conclusion, adding to the body of knowledge for high school athletes. The only reach direction affected by fatigue in my study was in the anterior direction and the effect size was very small. The reduction in distance for the anterior reach was 1.3 cm for the RLE and 1.6 cm for the LLE.

Even though these reduced distances for anterior reach after fatigue represent a small effect size of limited clinical value, it is interesting to note that the anterior reach direction being affected (and not other reach directions) is consistent with other research investigating asymmetry between legs. Those studies identify that a 4 cm asymmetry in the anterior direction can predict sport injury (P. J. Plisky et al., 2006; C. A. Smith et al., 2015). Asymmetry of other research directions have not shown to be consistently predictive of injury. The anterior reach requires the athlete to balance on the stance leg with increasing knee flexion as the reach leg moves forward. During this maneuver, the trunk remains mostly above the stance foot. Therefore, there is little posteriorly directed ‘counterbalancing’ by the trunk to the body mass of the reaching leg moving forward. Contrary to this, for the posteromedial and posterolateral reaches, the trunk moves forward as the reach leg moves posteriorly, providing a counterbalance to each other. See figure 2 for typical reaching postures. This counterbalancing aids in keeping the center of mass within the stance foot. Perhaps the counterbalancing afforded the posteromedial and posterolateral reach directions is able to off- set fatigue- induced reduction in postural stability as compared to the anterior directed reach.

Figure 2. Trunk Postures during Reaching



Fatigue protocols

Older research investigating fatigue and postural stability used laboratory based fatigue protocols such as isokinetic resisted muscle activity (Gribble et al., 2004; Salavati et al., 2007). More recent fatigue research utilizes functional movement protocols such as shuttle runs, sprints and step ups which propose to induce whole body fatigue (Baghbaninaghadehi et al., 2016;

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Hosseinimehr, 2010; Pau et al., 2014) Only one study was found that utilized a fatigue protocol planned to be similar to what athletes perform during sport activity. Lacey and Donne (Lacey & Donne, 2019) utilized a 60 min zig-zag running protocol at intermittent percentages of 50-95% maximum running velocity to fatigue athletes. They argue theirs is the first study to use a fatigue protocol that well replicates a game length, and game activities where athletes have episodes of high intensity non-linear running intermittent with lower intensities. The authors hypothesized their game simulating scenario would result in fatigue induced deficits in dynamic postural stability. However, their fatigue protocol did not result in reduced reach distances measured by the YBT-LQ. To my knowledge, my study is the first to investigate the effect of fatigue induced by participation in actual sport specific activities during a practice session at the sport field of play. The conclusion of my study is consistent with the results of the prior described study simulating a game scenario.

Fatigue and gender

There are findings in other studies of females performing better than males when fatigued (Abdelkader et al., 2021; Alnahdi et al., 2015; Onate et al., 2018) but contrary to this, my study found no difference in fatigued performance by females as compared to males when gender was directly statistically analyzed. A meta-analysis study found non-fatigued differences based on gender for the posteromedial and posterolateral directions but not for the anterior or composite reaches (P. Plisky et al., 2021). Since my study found only the anterior direction to be affected by the fatigue protocol I used, this may explain the discrepancy of my findings to other gender comparing studies. The meta-analysis suggested that gender differences may be specific to sport

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participation and competition level but that heterogeneity of the studies included in the meta-analysis didn't allow investigation of these gender by sport and gender by competition level combinations. My research did find differences in the pattern of fatigue based on gender when sport participation was also considered. The omnibus one-way ANOVA for female athletes competing in different sports showed differences in fatigued performance for 6 of the 8 reach variables (right and left leg, 3 directions and composites = 8 reach variables) while the males had difference in performance for only 2 of the 8 reach variables.

Fatigue and sport participation

My research found that participation in a specific sport did affect fatigued dynamic postural stability differently from other sports, and the effects were medium to large. Interestingly, only Lacrosse participation had the expected reduction in performance when fatigued consistent across all reach variables. Participation in basketball and soccer showed some reach variables improved in performance and some regressed with fatigue although not similarly to each sport. Baseball/softball players both had improved performance with fatigue. Lacrosse, basketball and soccer players often utilize unilateral stance maneuvering so it is understandable that these would show fatigue effects when using the YBT-LQ for measuring dynamic postural stability. The improved scores for baseball/softball players seems counterintuitive given that sport does not utilize unilateral stance routinely although weight shifting toward one leg does occur. The meta-analysis referenced above (P. Plisky et al., 2021) found that baseball players had greater reach distances on the YBT-LQ compared to basketball players. The authors of the meta-analysis proposed that body anthropometrics may explain some

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of the variance in athletes' performance on postural stability measured by the YBT-LQ. Their example was that basketball players in general are taller than athletes in other sports (Wood, 2008; Zhao et al., 2019). A taller athlete would have a higher center of mass making postural stability more difficult during single leg stance. Differences in height, body mass distribution and leg muscle circumference have been found among athletes (including high school athletes) participating in different sports (Radu et al., 2015; Sánchez Muñoz et al., 2020; D. A. Santos et al., 2014). It is feasible that the baseball/softball players in my study differed in body type to athletes of other sports. This difference may explain improved post fatigue postural stability in both male and female ball and bat players. I agree with the authors of the meta-analysis that sport specific normative values using dynamic measurement procedures including the YBT-LQ are needed, and I further suggest fatigue be included in these sport specific investigations.

Limitations

Participants did not do a formal warm up including flexibility maneuvers prior to the pre-fatigue data collection. This may have resulted in reduced pre fatigue reach distances and result in distances closer to post fatigue measures and thereby not identified statistically. Initially, a warm up activity was planned. However, the logistics of scheduling a team of high school athletes to come early to practice were unsurmountable given school requirement that school personnel must accompany the investigator when with athletes. While a formal warm up was not completed, each athlete did participate in practice reaches to become familiar with the YBT-LQ testing procedures. Each athlete practiced at least 3 trials for each reach direction on each leg

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equaling at least 18 maneuvers taking 3-4 minutes. It is expected that the practice session adequately served as both a muscle action and flexibility warm up.

The wearing of shoes in this study prevents the comparison of its normative and fatigue data to studies without shoe wearing during YBT-LQ testing. Unfortunately, the 2 very recent review articles published in 2021 (one a systematic review (Abdelkader et al., 2021), the other a meta-analysis (P. Plisky et al., 2021)) do not report findings by shoe wearing or not.

A final concern is that except for the lacrosse athletes, adequate fatigue may not have been reached during the sport specific practice session led by the specific sport team coaches. The Borg RPE 20 has limitations for use in adolescents in the lower range of the scale but is known to correlate well to peak oxygen consumption for values of at least 13 (Tolusso et al., 2018). The Borg RPE value of 14 is known to correlate to the second lactate threshold which is the threshold at which anaerobic metabolism begins to contribute to blood lactate (Scherr et al., 2013). The study in which this RPE to blood lactate relationship was established included youth athletes 15-18 years old. The relationship between RPE and neuromuscular fatigue has been investigated in adults. A study of quadriceps muscle activity during constant load cycling calculated a neuromuscular fatigue threshold based on EMG and RPE data (Fontes et al., 2010). A linear relationship of R2 = 0.69 (medium goodness of fit) was found between RPE values and fatigue to neuromuscular exhaustion. Another study investigated the relationship between EMG values of the rectus abdominus muscle during a plank exercise to complete fatigue (Cruz-Montecinos et al., 2019) These investigators found an RPE of 5 on the Borg CR10 scale correlated highly (r=.85, 95% CI = 0.77–0.93) with fatigue of the RA muscle. The Borg CR10 score of 5 relates to a Borg RPE score of 14 (Arney et al., 2019). The average RPE reported by

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the athletes in the current study was 14.8 (1.3 sd) and 90% of the participants reported an RPE greater than 13. Other studies investigating fatigue consistently used an RPE of at least 15 as the Borg RPE exertion level to attain (Baghbaninaghadehi et al., 2013; Benjaminse et al., 2008; Zech et al., 2012).

Implications

The anterior reach direction has surfaced as the direction of importance in prior studies using the YBT-LQ to measure postural stability. This direction of reach was the only direction where fatigue was found to have an effect (albeit small) in the current study for both males and females. The consistency of the anterior direction findings across research, including this study, implicates it is a focus for decision making about an athlete's readiness to play whether fatigued or not. The anterior reach maneuver is similar to when an athlete kicks a ball forward and also when landing but quickly turning toward the stance leg to change direction, like happens in sports such as basketball and lacrosse.

My study identified Lacrosse as the sport most consistently effected by a reduction in dynamic postural stability caused by fatigue for both females and males. According to Sports Destination Management, a publication written for sports event organizers, participation in lacrosse at all levels has increased over 200% for both females and males from 2001 to 2017 (Leand, 2019). Statista reports high school athletes made up 40% of these players in 2018, consisting of 186,335 males and 145,882 females (Statista, 2018). The availability to have normative data for pre and post fatigue specific to lacrosse is invaluable given the rise in lacrosse teams in high schools. The most frequent injury for male high school lacrosse players is contact with a stick (14.8%) but in females, overuse injuries (25%) are most common (Warner et al.,

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2018). Serious injury to the knee has been reported for high school lacrosse players with the proportion of knee injuries treated with surgery for female lacrosse players is 39.3% and 25% for males (Swenson et al., 2013). The addition of this study's lacrosse specific normative data for the 3 reach directions to already available normative data will be valuable for return to sport after injury decisions. A normative data set that is age, sex and sport specific provides sports medicine and team athletic personnel with reference points to compare to their athlete's performance. If a gap shows an athlete's fatigued postural stability is lower than normative values, it indicates the athlete's performance is abnormal compared to age, gender and sport matched peer athletes. An abnormally low fatigue performance indicates an athlete is not ready to return to play after an injury or needs to rest during competition. Numerous investigators have called for the development of population specific and large normative data sets including for youth athletes (Alnahdi et al., 2015; Butler et al., 2012; de Noronha et al., 2013; González-Fernández et al., 2022; Lisman et al., 2018; Onate et al., 2018; Powell et al., 2018, 2018; Teyhen et al., 2016)

Recommendation for Future Research

It would be informative to identify if there is a difference in postural stability measured with the YBT-LQ when wearing shoes as opposed to being barefoot. Initially an investigation comparing the shod vs unshod condition in healthy individuals would generally identify if shoes had an effect on postural stability with this measurement device. Given that we know athletic shoe wearing improves postural stability from prior research it is likely that an effect will be

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found. If so, additional inquiry into other populations is warranted: youth vs adult athletes, injured vs non-injured athletes.

There has been a call for sport specific fatigue protocols be used in research studies about fatigue effects. So, another important area of fatigue research would be to formally investigate coaching led practice sessions to identify what sport specific training typically occurs and the amount of fatigue a component of training results in. This could be compared to the fatigue induced by actual sport competition. This information would be useful for coaches and athletic trainers when planning practices so that the actual 'fatigue tolerance' needed to prevent injury is developed during practices. Another comparison could be to compare fatigue effect on dynamic postural stability of non-sport specific fatigue protocols to the sport specific fatigue effect to see if sport specific protocols make a difference in the first place.

Conclusion:

When the data from all athletes was analyzed, this study showed only a very small fatigue effect on dynamic postural stability when any effect was found at all. This study did not support the hypothesis that female athletes in general are more resistant to a reduction in postural stability when fatigued as compared to male athletes. When fatigue induced postural stability was analyzed based on sport participation, fatigue effects were medium to large. However, only Lacrosse athlete, both male and female, were found to experience a reduced postural stability when fatigued. A significant limitation of the generalizability of this study's findings is the possibility that the coach led practice sessions did not induce enough fatigue to effect postural stability compared to fatigue induced during actual play.

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Appendix A. Coach Information Sheet

Can injury be predicted in your athletes?

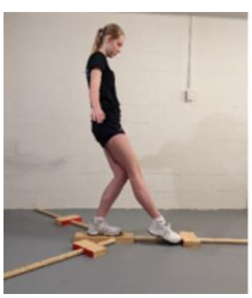
Research shows that athletes with less balance when standing on one leg have an increased risk of injury during play. We also know that balance decreases when an athlete becomes fatigued. I am from the Physical Therapy Program at Youngstown State University and I want to add to what is known about fatigue and athletes. For example, we need to know if balance changes the same for female and male athletes. OR if balance changes differently when fatigued depending on the sport played. If you agree, I would like to ask your athletes to help us with the project.

What I will do:

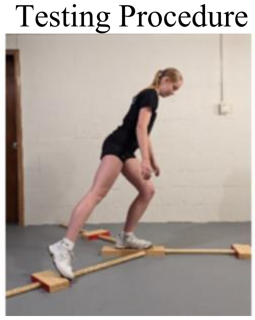
- I will come to your facility and ask your athletes to allow us to measure their balance before and after their legs get tired from typical activities you have them do during a practice session. I will compare the balance scores of the before fatigue to those taken after the athlete is fatigued by your practice activities.
- I will not change anything you want the athlete to do (or not do) during practice or games. If your athlete is less than 18 years old, I will only measure the athlete if the parent also gives permission.
- Measurement takes about 10 minutes per athlete using the balance board (picture below).
- Two measurements of balance will occur on the same practice day. I will come to the beginning of one of your practice sessions to test each volunteer athlete before s/he participates in your practice. At the end of the practice or when the athlete feels 'hard exertion' I will retest the athlete for balance.

I have received support from your school's administrators (superintendent and athletic director) to talk with you about this project. This project has been approved by YSU's research review board to allow research with children. If you agree that I can do this with your team I will first need to come meet your athletes to explain the project and to provide them with a parental consent form. This first session will take less than 10 minutes with your team.
To schedule a session to meet your athletes or to answer your questions I can be reached at**:**
Cathy Bieber Parrott #330 941 2559 or at cbieberparrott@ysu.edu.

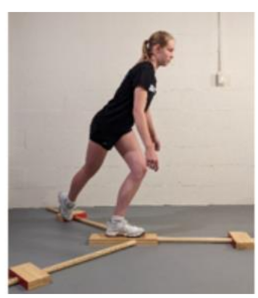
Testing Procedure



Anterior



Posterolateral



Posteromedial

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Appendix B. Demographic form

Demographic Information

Name: ___________________________________

Assigned research identification number ___________ (to be completed by researchers)

Position played on the team ___________________________________

Circle: Male or Female

Age: ____________

List all <u>organized Team Sports</u> played each year (track, basketball, baseball/softball, tennis, etc)
____

List all other physical activity you regularly participate in (regularly is at least 3 times/week). Examples are jogging, weight lifting, rock climbing.

____

List all previous injuries to bone, muscle or joint which required it to be checked out by a physician in the last year.

Injured area ____ how long ago? ______

Injured area ____ how long ago? ______

Injured area ____ how long ago? ______

Injured area ____ how long ago? ______

Injured area ____ how long ago? ______

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Appendix C. Data Collection Form

Athlete ID number	Leg Length in cm for right leg		Pre-YBT						RPE Fatigue Score	Post-YBT						Comments
			Right stance Leg trial			Left stance leg trial				Right stance Leg trial			Left stance leg trial			
	RLE LLE	Y dir	1st	2nd	3rd	1st	2nd	3rd		1st	2nd	3rd	1st	2nd	3rd	
		AP PM PL														
		AP PM PL														
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Appendix D. Borg Rating of Perceived Exertion

How you might describe your exertion	**Borg rating of your exertion**	**Examples (for most adults <65 years old)**
None	6	Reading a book, watching television
Very, very light	7 to 8	Tying shoes
Very light	9 to 10	Chores like folding clothes that seem to take little effort
Fairly light	11 to 12	Walking through the grocery store or other activities that require some effort but not enough to speed up your breathing
Somewhat hard	13 to 14	Brisk walking or other activities that require moderate effort and speed your heart rate and breathing but don't make you out of breath
Hard	15 to 16	Bicycling, swimming, or other activities that take vigorous effort and get the heart pounding and make breathing very fast
Very hard	17 to 18	The highest level of activity you can sustain
Very, very hard	19 to 20	A finishing kick in a race or other burst of activity that you can't maintain for long

Appendix E. YSU Institutional Review Board Approval

YOUNGSTOWN STATE UNIVERSITY

One University Plaza, Youngstown, Ohio 44555
Office of Research
330.941.2377

November 1, 2018

Ms. Cathy Bieber Parrott, Principal Investigator
Department of Physical Therapy
UNIVERSITY

RE: HSRC PROTOCOL NUMBER: 056-2019
PROTOCOL TITLE: Predicting Sport Injury with the Y-Balance Test

Dear Dr. Bieber Parrott:

The Human Subjects Research Committee of Youngstown State University has reviewed the above mentioned protocol via Full Committee Review and determined that it fully meets YSU Human Subjects Research Guidelines. Therefore, I am pleased to inform you that your project has been fully approved for one year. You must submit a Continuing Review Form and have your project approved by October 31, 2019, if your project continues beyond one year.

Any changes in your research activity should be promptly reported to the Institutional Review Board and may not be initiated without IRB approval except where necessary to eliminate hazard to human subjects. Any unanticipated problems involving risks to subjects should also be promptly reported to the IRB.

S

Dr. Gregory Dillon
Interim Associate Vice President for Research
Authorized Institutional Official