THE INFLUENCE OF LOWER EXTREMITY MOVEMENT QUALITY AND BODY COMPOSITION ON LOWER EXTREMITY BONE STRESS INJURY OCCURRENCE IN DIVISION I CROSS COUNTRY ATHLETES

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ABSTRACT

Yana I. Ginzburg: The Influence of Lower Extremity Movement Quality and Body Composition on Lower Extremity Bone Stress Injury Occurrence in Division I Cross Country Runners
(Under the direction of Darin A. Padua)

Bone stress injuries (BSIs) are prevalent among cross-country athletes. This study aims to identify lower extremity movement quality and body composition characteristics that influence BSIs. 37 collegiate cross-country athletes were tested at preseason. Biomechanical data were obtained through visual observation of overhead and single leg squats. Body composition data were gathered via Dual-Energy X-Ray Absorptiometry scans. Injury data were recorded in an electronic medical record for one year post-testing. Chi-square analyses examined biomechanical data, and independent samples t-tests examined body composition data. Females and athletes with a lower BMI, lower mass, and lower lean mass are more likely to sustain a BSI. Injured leg lean mass was less than leg lean mass of uninjured athletes. Biomechanical assessments were unable to discern between the two groups. Females and athletes with low BMI or small lower extremity lean mass should be monitored for implementation of injury prevention programs to mitigate BSI occurrence.

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LIST OF ABBREVIATIONS

BSI	Bone Stress Injury (Stress Reactions and Stress Fractures)
DEXA	Dual Energy X-Ray Absorptiometry
EMR	Electronic Medical Record
OHS	Overhead Squat
PFP	Patellofemoral Pain
SLS	Single Leg Squat

CHAPTER I

INTRODUCTION

1.1 – Background

Lower extremity injuries are detrimental to a runner's well-being, and have implications that are physical, psychological, and financial. Physical costs include decreased performance and quality of life.[1] Psychological effects may include mood disturbances, depression, and loss of self-esteem.[2] Little data is present on the financial costs of lower extremity injuries in runners, but for only one particular injury they may be potentially as high as $376 million per year or greater.[3]

Running is a repetitive activity. The foot contacts the ground between 50 and 70 times per minute, amounting to a colossal 800 to 2,000 times per mile.[4] The legs and back absorb forces between 3 and 8 times the body weight of the individual during each foot strike.[4] These forces have a direct effect on lower extremity injuries in cross-country runners.[4] Biomechanical abnormalities are exacerbated during running and can result in an aberrant running gait.[4] Thus, chronic lower extremity overuse injuries in distance runners are frequent. Overuse lower leg, knee, and ankle injuries are most frequently reported. Jointly, these injuries comprise nearly two-thirds of all running related injuries.[5] Stress fractures are one of the most frequent conditions.[6-8] A stress fracture is characterized by the gradual but incomplete break of bone;[9] this condition is one that progresses from a stress reaction if the symptoms are not identified early enough or if the stress reaction is left untreated.[10] A stress reaction is defined as the exposal of bone to unusual stress that results in pain and tenderness.[11] Among Division I collegiate athletes, track and cross country athletes are one of groups of athletes most frequently affected by stress fractures.[12] Bone stress injuries include both stress reactions and stress fractures.

Common stress bone stress injury sites include the metatarsals and the medial portion of the tibia.[13] In seasoned runners, these injuries commonly occur following alterations in running habits – which may include alterations in running volume, changes in the route the individual is running, or different shoes.[14] With proper preventative measures, bone stress injuries are preventable lower extremity injuries.[15] Once diagnosed however, rest is essential to allow adequate time for the bone reformation process to occur. If the athlete does not take adequate rest, there is potential for the stress reaction to progress to a stress fracture[10] to then to turn into a complete fracture of the bone.[14]

Preseason screenings can determine an athlete's likelihood of lower extremity injury.[16,17] Functional movement testing can determine an athlete's lower extremity neuromuscular control during various movement assessments.[18] In particular, the single leg squat[19] and the overhead squat[20] are valid measures of identifying an individual's aberrant biomechanical patterns. Additionally, knowing an athlete's body composition may be useful in predicting lower extremity injuries.[21] To determine an athlete's body composition, Dual-Energy X-Ray Absorptiometry (DEXA) is a recommended method.[22,23]

Due to the high volume of lower extremity injuries in runners, it is imperative that steps be taken to identify individuals likely to incur bone stress injuries in order to mitigate their potential for injury. To date, no study has investigated the influence of preseason movement assessments utilizing clinical evaluations such as the single leg squat and overhead squat, and DEXA body composition information on bone stress injury development in Division I cross country athletes. Thus, the first aim of this study was to determine how lower extremity movement patterns differ between runners who go on to sustain a lower extremity bone stress injury and those who do not. The second aim of this study was to examine the differences in means between injured and uninjured groups in relation to various body composition variables as determined by DEXA.

1.2 – Statement of Problems and Hypotheses

1) *Research Question 1:* What are the effects of lower extremity movement patterns, as measured by visually observed clinical movement assessments, on bone stress injury frequency among collegiate cross-country athletes?
    i. *Research Question 1a*: What are the effects of lower extremity movement patterns, as measured by the overhead squat, on bone stress injury frequency among collegiate cross-country athletes?
        - *Hypothesis:* Athletes who go on to sustain a bone stress injury will have more abnormal movement patterns in their overhead squat preseason assessments.

ii. *Research Question 1b*: What are the effects of lower extremity movement patterns, as measured by the single leg squat, on bone stress injury frequency among collegiate cross-country athletes?

  - *Hypothesis:* Athletes who go on to sustain a bone stress injury will have more abnormal movement patterns in their single leg squat preseason assessments.

2) *Research question 2:* What are the effects of body composition, as measured by Dual Energy X-ray Absorptiometry (DEXA), on bone stress injury frequency among collegiate cross-country runners?

   i. *Research question 2a:* What are the effects of a low bone mineral density on bone stress injury frequency among collegiate cross-country runners?

      - *Hypothesis:* Athletes who go on to sustain a bone stress injury will have lower than average bone mineral density in their preseason assessments.

   ii. *Research question 2b:* What are the effects of lean mass on bone stress injury frequency among collegiate cross-country runners?

      - *Hypothesis:* Athletes who go on to sustain a bone stress injury will have lower than average amounts of lean mass in their preseason assessments.

   iii. *Research question 2c:* What are the effects of percent body fat on bone stress injury frequency among collegiate cross-country runners?

- *<u>Hypothesis</u>:* Athletes who go on to sustain a bone stress injury will have lower than average amounts of body fat in their preseason assessments.

1.3 – Variables

1.3a – Independent variables

1) Movement patterns during the overhead squat
   a. Foot turns out
   b. Foot flattens
   c. Knee valgus
   d. Knee varus
   e. Forward lean
   f. Low back arching
   g. Low back rounding
   h. Arms forward
   i. Heel lift
   j. Weight shift
2) Movement patterns during the single leg squat
   a. Foot flattens
   b. Knee valgus
   c. Knee varus
   d. Trunk hip shift

    e. Loss of balance
    f. Knee flexion <60°
    g. Low back rounding
    h. Trunk flexion rotation
    i. Hip drop or hike
3) Body composition
    a. Bone mineral density
    b. Lean mass
    c. Percent body fat

1.3b – Dependent variable

1) Bone Stress injury (stress fracture or reaction)
2) No bone stress injury (stress fracture or reaction)

1.4 – Definition of Terms

1) Stress reaction: exposure of a bone to unusual stress that results in pain and tenderness but is reversible.[11]
2) Stress fracture: a gradual but incomplete break of the bone, resulting from its inability to withstand repeated excessive forces. For diagnosis, requires that an originally normal bone experience no direct trauma but rather progressive causal activity, pain and tenderness, and show proof of remodeling on follow-up x-rays.[9] It is differentiated from a stress reaction by passage of time.[11]

CHAPTER II

REVIEW OF LITERATURE

2.1 – Introduction

Lower extremity overuse injuries are rampant in elite athletes, and elite cross-country runners are no exception. In particular, an analysis published in 2015 reviewing quality scholarly journal articles found that over the course of a 13 week season, about 19.7% of cross country runners had a time loss injury. The lower leg was the most affected area at 30.3% of all injuries, followed by the knee at 22.5% and the ankle at 16.2%.[5] The total incidence of running overuse injuries was found to be 0.0675 per 1000 km of running exposure;[24] to contextualize this exposure, a study of young female cross-country runners found that the average weekly distance ran was 55.5±18.0 kilometers per week.[25]

There is no overall consensus as to whether males or females are more likely to get injured. An argument has been made for analyzing the rates of injury by type of injury in addition to sex.[8] However, discrepancies are present in the various data available. A 1991 clinical case study conducted over a 4-year period by Macintyre et al.[7] reported little difference in types of injuries between men and women. However, a 2002 retrospective case-control analysis conducted over a 2-year period by Taunton et al.[8] found that males were more likely to exhibit higher rates of plantar fasciitis and Achilles tendonitis, whereas women were more likely to be affected by patellofemoral pain. Thus, with differing information present, there is no clear indication of whether one sex is more likely to get injured than the other.

The cost of lower extremity overuse injuries is extremely varied. However, each different type of injury bears a burden on the individuals it affects. These burdens are both financial and physical. Financial costs of lower extremity overuse injuries can be broken down into two categories – direct medical costs and reduced productivity costs. The first category of direct medical costs includes services delivered by a physician, physical therapist, or other specialist. This also includes expenses for diagnostic imaging, medications, and disposables used by these healthcare providers. The second category of reduced productivity costs refers to the amount of money lost at work due to the individual's inability to perform at his/her full capacity. This may be as severe as the total absence from work.[1] Data for these costs are lacking. However, as of 2007, the fiscal liability of patellofemoral pain in the US due to treatment costs alone was $192 to $376 million.[3]

Physical costs of lower extremity overuse injuries result in a decreased quality of life. This is due to the injury's impacts on the individual's mobility, ability to care of oneself, activity levels, pain, and anxiety.[1] Lower extremity overuse injuries frequently occur in young individuals who exercise vigorously. There have been suggestions that high intensity and high mileage running may be predisposing factors for premature osteoarthritis of the hip[26] as well as possible nerve damage in the feet,[27] indicating long term negative effects on young individuals that will cause a lifetime of problems.

Previous lower extremity injury history has been a clear indicator of the high likelihood for future lower extremity injury.[28,29] An estimated 31% of runners incur the same injury as previously, although they may have completed a rehabilitation program.[24] This may be due to the fact that the runner continues to incur faulty movement patterns, which lead to tissue overload, cause functional adaptations, and ultimately lead to tissue damage and injury.[30] Eventually, these structural and biomechanical changes become permanent and continue to increase the future possibility for lower extremity injury.[31]

A lower extremity overuse injury presents as tenderness and pain in a particular area when no evident trauma has occurred.[32] It is a problem caused by running that limits the individual in speed, distance, length, or frequency for 7 days or more.[33] The causes of lower extremity overuse injuries are multifactorial and vary with each type of injury,[30] but are generally attributable to the accumulation of repeated overloading of ground reaction forces upon the musculoskeletal system.[34] The most frequent types of lower extremity overuse injuries seen in runners are stress fractures, patellofemoral pain, plantar fasciitis, and Achilles tendonitis.[6-8]

Stress fractures are the product of repetitive mechanical loading,[35] with the bone undergoing a weakening and periosteal reaction due to the large amounts of stress.[36] This type of lower extremity overuse injury is frequently found in veteran runners who are increasing their distance or intensity of run.[37] In addition, it is also frequently found in those who are simply novice runners, or novice runners who add mileage to their training regimes too quickly. These individuals tend to exceed the bone threshold for damage too soon, providing inadequate recovery time for the bone and resulting in a strain that is not attenuated over time.[35] Ultimately, the question of whether a runner develops a stress fracture is also dependent upon his or her collection of overall factors, as not all runners of the same level exposed to the same training regime will go on to develop a stress fracture.[35]

Most stress fractures have been found to be associated with an abnormal foot arch – such as pes planus (low static arch index) and pes cavus (high dynamic arch index).[38] Other factors include limited ankle dorsiflexion and knee varus alignment.[39] The two main types of stress fractures are metatarsal stress fractures and medial tibial stress fractures.[13]

Metatarsal stress fractures are the most common affliction of the foot,[40] with the second, third, and fourth metatarsals most frequently affected.[41] This particular type of stress fracture has been found to be associated with increased hind foot inversion[38] as well as a loading of the plantar flexors and Achilles tendon.[34] In addition, Hughes et al.[36] found that individuals with a notable decrease in ankle dorsiflexion were 4.6 times more likely to develop a metatarsal stress fracture when compared to their full range of motion counterparts.

Tibial stress fractures are another common type of stress fracture, frequently occurring on the compression side of the tibia[42] and found to be correlated with altered loading.[43] This altered loading leads to accumulated force loads over time,[44] which create a bone stress reaction that results in pain.[45] This injury may be associated with knee valgus[13,46] as well as an external hip rotation range of motion measurement above 65 degrees.[46] In addition, shorter tibial bone length has also been implicated – as shorter tibias tend to be narrower and therefore unable to withstand the amounts of compression, tension, and torsional forces of longer tibias.[13,42] Rearfoot eversion has also been found as an association.[42] Running competitively may also predispose an individual to a tibial stress fractures, as their incidence is found at a higher rate in elite runners when compared to recreational runners.[13]

Patellofemoral pain (PFP) is commonly observed in long-distance runners, with an incidence rate of 0.0135 injuries per 1000km run.[24] Abnormal joint ranges of motion causing biomechanical compensations have been implicated[47] – such as excessive active hip adduction range of motion,[48] limited active ranges of motion in the hip internal and excessive hip external rotations[39] as well as limited ankle dorsiflexion.[47] In addition, there is an association between large quadriceps angles (Q-angles) and patellofemoral pain. A larger than normal Q-angle may laterally displace the patella as the quadriceps muscles contract, pressing it against the lateral femoral condyle and leading to discomfort.[49] Additionally, running with a rear foot (heel) strike pattern may increase joint stress.[50,51] This is due to the fact that at impact, the body of a heel striker receives a high impact strike that is approximately 1.5-3 times the individual's body mass – leaving little time and therefore ability for the body to reduce the immense forces traveling up the kinetic chain[51] – and specifically, to the patellofemoral joint.[50]

Plantar fasciitis is a pain or stiffness in the arch of the foot exacerbated by activity,[52] occurring at a rate of 0.0037 injuries per 1000km run.[24] The plantar fascia plays a major role in maintaining the medial longitudinal arch.[38] Plantar fasciitis is associated with a flawed ankle range of motion, such as excessive plantar flexion[53] and limited dorsiflexion.[54] This may lead to excess loading of the plantar-flexor muscles as well as the Achilles tendon.[34] Excessive pronation increases tensile stresses to the plantar fascia insertion,[54] also adding unnecessary stresses. Peak torque deficits of the plantar flexor muscles have also been implicated; thus, strength deficiencies play a role in plantar fasciitis, although it is not clear whether they are the cause or the result.[54]

Achilles tendonitis is the most common lower extremity overuse injury, occurring at a rate of 0.0159 injuries per 1000km run.[24] It typically presents itself as pain along the Achilles tendon and its insertion, potentially with or without swelling[55] and frequently occurs in veteran runners[56] with 10 or more years of running experience.[24] The Achilles tendon acts as a biological spring, stretching during the initial portion of the run cycle and recoiling at push off to provide the runner with energy in movement[55]. There are several factors that have been implicated with Achilles tendonitis. It is correlated with a tight gastrocnemius and increased hind foot eversion, the latter due to the lack of attenuation for the loading of mechanical forces on the Achilles tendon.[38] Contrastingly, when the hind foot is in proper form, regional stresses can be brought superiorly up the kinetic chain and ultimately decrease the force of impact.[55] Additionally, forefoot striking has been found to also increase Achilles tendon loading[50] as well as that of the plantar-flexors.[34] A tight gastrocnemius is also implicated, as evidenced by a limited ankle dorsiflexion range of motion.[38,56,57]

2.2 – Predisposing Factors

Predisposing factors that influence runners to the aforementioned lower extremity overuse injuries can be broken down into intrinsic and extrinsic. Intrinsic factors are internal and originate within the body,[58] and include the individual's biomechanics – both kinematics and kinetics – as well as anatomy.[32] Extrinsic factors are external,[58] and include factors such as the individual's training regime.[32] The amount that each factor contributes to a runner's lower extremity overuse injury varies depending on the individual.[35] Overall, these factors cause alterations in the runner's body that necessitate compensatory changes, and reduce the body's overall mechanical efficiency.[41]

Biomechanical kinematics is the analysis of body movements, disregarding the forces acting on the body that cause those movements.[55] Kinematics can be considered an individual's geometry of movement. The biomechanical kinematic factors that predispose runners to lower extremity injury include the magnitude of foot pronation as well as inadequate hip stabilization.[39]

Foot pronation is a normal part of movement. However, when it is excessive or occurs at the wrong time – such as in place of foot supination – issues arise.[59] Excessive pronation tends to occur as a compensation for limited ankle dorsiflexion range of motion.[39] As the deviations in pronation occur, they lead to deviations in internal tibial torsion, and ultimately create a strain on the lower extremity soft tissues[59] – in particular, on the medial knee.[60] Thus, excessive pronation is associated with stress fracture development due to its generation of undue torques and subsequent ankle instability.[30] An additional cause for excessive pronation is also femoral anteversion.[39] Femoral anteversion is an inward rotation of the femoral neck in the acetabulum, and is associated with an excess in active hip internal rotation and a limitation in active hip external rotation.[39]

Inadequate hip stabilization is another kinematic factor for lower extremity injuries in runners. It may primarily be attributed to reduced hip muscle strength.[39] However, abnormal ranges of motion are also implicated. These include excessive active hip internal and restricted active hip external rotations, restricted active hip flexion,[39] as well as excessive passive hip adduction[48,61] and excessive active hip adduction[39] range of motions. Excessive hip adduction is theorized to act as a compensatory mechanism for weak gluteus medius and gluteus maximus muscles,[61] as well as potentially weak hip abductor muscles.[48] Mauntel et al.[61] proposed that the excessive hip adduction is due to a neuromuscular compensation for an inadequate ankle range of motion during functional tasks. Consequently, inadequate hip stabilization may occur due to the body's inability to fire muscles as necessary during functional tasks.

Kinetics deals with the forces that produce motion.[41] In relation to the biomechanics of runners, kinetic factors leading to lower extremity overuse injuries include the magnitude of impact forces as well as the rate of impact loading.

Impact forces are external stresses affecting the body, and in running generally refer to ground reaction forces.[62] Ground reaction forces can aid bones in building and maintaining structural integrity. However, ground reaction forces may excessively load bones and negatively impact bone remodeling.[63]

The magnitude of impact forces is a factor largely associated with potential for stress fractures. Heel striking, as opposed to forefoot striking, creates a significantly larger force for the body to attenuate – anywhere from 1.5 to 3 times the individual's body weight.[51] Over the course of a run, the repetitive motion of the foot hitting the ground places a great strain on the bone. The bone can withstand certain amounts of strain, and utilize the ground reaction forces to build the bone over an extended time period.[35] However, past a particular amount of stress, the bone begins to accumulate microscopic damage. Although the bone can typically heal itself after incurring such damage, under certain conditions – such as a large impact force combined with inadequate recovery time – it exceeds the tissue's capability to withstand damage and reaches an ultimate failure point where the bone tissue damage is irreversible.[35] Thus, repeated stresses below a tensile load with adequate time for recovery do not cause lower extremity injury; however, inadequate time,[33,64] as well as excessive peak impact force even if incurred in one particular instance,[65] result in an overuse lower extremity injury. This is frequently seen in long distance runners that undergo high numbers of impact forces due to the extended length of the runs, creating a cyclic overload of impact forces[35] that frequently affects performance.[63] The size of impact forces varies with velocity of movement and surface of the movement, but is generally a multiple of the body weight.[66] Ultimately, the effects of the large magnitudes of these forces also depend on the body's ability to react to applied loads.[35]

The rate of impact loading is another predisposing factor, as it lessens the runner's ability to cushion stresses (a protective mechanism).[44] The rate of impact loading refers to how fast the force acting on the body is altered.[66] Lower extremity injuries due to a high rate of impact loading are frequently seen in sprinters; these individuals are exposed to high magnitude loads in short periods of time, predisposing them to lower extremity overuse injuries that result from high rate impact loading.[35] The muscles act as shock absorbers during running and help offset forces that are transmitted proximally over the course of the runner's gait. When those muscles are weak, tight, or simply fatigued, their ability to offset impact forces is lessened and there are large stresses unnecessarily placed on the body.[35] High rates of impact loading are particularly detrimental when combined with improper body form.[35] When those stresses exceed the tissue's fatigue limit, injury may occur.[64]

An individual's anatomy also plays a role in the runner's potential for lower extremity injury. Anatomical predisposing factors include Body Mass Index (BMI), body composition, Q-angles, as well as muscular flexibility range of motion measurements. A bimodal relationship has been found between BMI and potential for injury.[67] Individuals with both high and low BMI's are at increased chances of incurring an injury, compared to those individuals who have an average BMI. Those with a high BMI and/or high percent body fat may place excess stresses on their musculoskeletal systems due to the additional weight.[67] However, those with a low BMI may not have enough lean mass to act protectively against lower extremity injury during physical activity.[67] This holds true for both men and women.[68] In particular, in women, a BMI of 21 kg/m^2 or smaller has been found to be a predisposing factor for certain types of injury; however, weighing below 60 kg is a protective factor against other injuries.[8] In addition, women were found to have a greater lower extremity injury predisposition at shorter heights, theoretically due to greater mechanical loading.[69] In men, a high percentage of body fat was correlated with lower extremity injury.[67]

Body composition can be determined using anthropometric measures such as DEXA scans.[21,23] Knowing information about a runner's body composition may help identify individuals with increased chances for developing an injury.[21] DEXA scans are used widely due to their precision, and provide information regarding bone mass, lean soft tissue, and fat contents.[23] However, its sources of error may include fluctuations in weight, body hydration, as well as content of the gastrointestinal juices and bladder.[70] In addition, changes in the amount of fat present local to a bone may can cause alterations in the reading of bone mass that are not actually present, with more fat increasing bone mineral density measurements and less fat decreasing the measurements.[23]

DEXA scans are able to measure total or regional bone mass.[23] The amount of an individual's bone mass is an important predisposing factor for lower extremity injury, as the ability of bone to withstand mechanical loads is dependent on bone structure as well as bone mass density.[35,71] Impact sports – such as running – have been found to produce a greater total skeletal mass when compared to non-impact sports – such as swimming.[63] When combined with adequate time for recovery, larger amounts of impact forces are able to stimulate greater bone growth; however, when combined with inadequate recovery time they may be detrimental to the bone's development.[63] Additionally, pelvis and leg regional bone mineral densities have been found to be greater in runners when compared to non-training individuals.[72] In particular, one study found that elite runners had a greater regional bone mineral density in the calcaneus when compared to soccer players as well as non-athletic sedentary controls.[73] Contrastingly, elite runners have also been found to have a lumbar bone mineral density so low that it is equivalent to osteopenia, although it is unclear whether this may be due to chance variation or due to issues inherent in the runner.[73]

The body of a runner can be described using the somatotypic theory, which opts to describe an individual's physique in terms of body shape and composition.[74] Elite runners are typically sometimes mesomorphs, although more typically ectomorphs.[75] Mesomorphs are typically muscular, whether visibly or with an obscure robustness; ectomorphs are those with a slender body type, frequently thin and lacking excess fat.[74] When compared to the average runner, an elite runner has more of his/her body weight as lean tissue.[75] This is beneficial, as too much fat tissue necessitates greater effort in accelerating the legs and thus utilizes too much increased energy expenditure.[76] However, insufficient lean tissue may have inadequate lean body mass to attenuate for the stresses of the forces involved in running.[77]

In males, body mass, right and left leg lean mass, bone mineral density, and bone mineral content have been found correlated with muscle cross sectional area.[21] An individual's muscle cross sectional area is an important area to consider due to its implications in absorption of impact forces as they travel up the kinetic chain over the course of a run.[35] A greater muscle cross sectional area attenuates the impact of force loads well, whereas a smaller one increases loading on bone.[35] Thus, attributes such as lower muscle cross sectional area – as well as weight - have been found to be associated with stress fractures.[21] In females, lean mass has been correlated with bone mineral density and bone mineral content.[21] Females with stress fractures have been found to have lower lean mass and higher percentage of body fat as well as lower muscle cross sectional area.[21]

An individual's Q-angle is measured by drawing an imaginary line from the intersection between the anterior superior iliac spine to the midpoint of the patella, as well as from the latter to the tibial tuberosity.[59] This measure is an accurate depiction of the quadriceps muscle force vector – although with a slight underestimation of the lateral force.[59] Large Q-angles are correlated with higher rates of lower extremity injury.[4,39] Although 20 degrees is commonly the upper boundary for normal values[4], some studies suggest a more conservative value and have found a correlation between patellofemoral pain and a Q-angle of 15-20 degrees.[49]

Lack of muscular flexibility is a predisposing factor for lower extremity injuries.[6] Inadequate flexibility may make a muscle more stiff than it otherwise would be, placing stress on its joints as compensation. This issue could also be indicative of a muscular imbalance, which would lead to early fatigue and altered biomechanics over the course of the run.[30]

Limited ranges of motion are causes for overcompensations that may cause lower extremity injuries.[39] In particular, limited active ankle dorsiflexion has been frequently implicated.[36] Restricted dorsiflexion ankle range of motion is a common problem in runners. The cause of this limitation may be tightness in the gastrocnemius, soleus, and capsular tissue.[39] The gastrocnemius assists in supination in the subtalar and midtarsal joints, so a tight gastrocnemius prevents the ankle from reaching the normal range of motion for dorsiflexion.[36] This leads to altered knee and joint movements – and can be visually observed as less knee flexion displacement and ankle dorsiflexion displacement during functional tasks such as the overhead squat and single leg squat.[78] In addition, this leads to increased knee valgus angle and medial knee displacement.[78,79] Ultimately, this range of motion constraint leads to internal tibial torsion[61] as well as foot pronation, both aspects of poor biomechanical patterns that predispose runners to lower extremity overuse injury.[36,61]

A runner's training may be a major predisposing factor for lower extremity overuse injuries. In particular, high running frequency and excessive distance have a large impact, as do sudden changes in training routines and high volumes of intense runs. The number of days per week[80] as well as the distance[56,80] an individual runs are predisposing factors for lower extremity overuse injuries. This includes high frequency and mileage as well as running very little.[29,31] Individuals running long distances frequently have higher rates of injury due to their exposure rate; however, those factors may also act as a protective mechanism – on the tissue as well as biomechanical levels – due to a musculoskeletal adaptive process that results in a decreased chance of injury.[28,81] However, frequent runs of long distances do not allow for adequate recovery and ultimately inhibit the bone remodeling process, acting detrimentally to cause bone tissue damage that enables the further accumulation of damage that may become permanent.[35,82] It is specifically the distance ran – not the amount of time spent running – that may increase an athlete's chance of injury, as the latter has been found to not be associated with lower extremity injury.[80] Contrastingly, running very little may be a predisposing factor as amateur runners frequently partake in training that exceeds their adaptive structural response;[6] this may also hold true due to a novice runner's poor technique.[83] Ultimately, it has also been theorized that while there is a correlation between running frequency and distance and lower extremity injury, those increased injury variables interact with other factors – such as the runner's biomechanics and anatomy.[4] While a runner may meet the intrinsic criteria for a lower extremity injury, the individual may be asymptomatic until his/her mileage hits an extrinsic threshold level that leads the musculoskeletal system to mark the excessive stresses as injury.[4]

Sudden changes in training routines are also predisposing factors,[56] due to the fact that these changes alter the rate of strain at particular sites[35] as well as the actions that muscles use to attenuate those strains.[14] In addition, an increased number of competitive runs[80] has been associaed, potentially due to overtraining.

2.3 – Movement Assessments

The single leg squat (SLS) is clinically used in conjunction with other movement assessments to identify individuals' neuromuscular control; when standardized,[18] it can be a tool for identifying flawed lower extremity movement patterns.[19] It has been found to be a reliable and valid clinical assessment.[84] It is valuable because it illustrates placement of knee alignment during weight bearing activities[85] and can be easily used to investigate the individual's hip strength and trunk control.[86] It may also be indicative of hip abductor musculature dysfunction[84] and is a good indicator of movement differences between males and females.[86] Furthermore, there are components of everyday movement that are evidenced in aspects of the single leg squat.[87] Lastly, it is overall a good representation of runner's movement patterns during the flight phase of running, as approximately 40% of time is spent in the swing portion.[88]

The overhead squat (OHS) is useful for analyzing body alignment[79] and has been found to be a valid tool for overall qualitatively assessing poor movement patterns.[89] It is particularly useful when utilized in conjunction with range of motion and strength measurements.[89] When the participant is performing an overhead squat, he is observed from three areas: anterior, lateral, and posterior.[89] In the anterior view, the clinician should assess the first MTP and the knee.[89] In the lateral view, the clinician should assess the extent to which the participant leans forward and lets his arms fall anteriorly.[89] In the posterior view, the clinician can observe excessive pronation as well as the extent of medial longitudinal arch collapse.[89]

In the lateral view, the overhead squat task is used to ascertain medial knee displacement,[90] which is useful in representing body misalignment during a run.[79] Medial knee displacement over the course of a run creates a situation with high impact stresses for repeated loading cycles.[63] It is known to be associated with either a medial gastrocnemius weakness,[90] limited ankle dorsiflexion,[20] as well as greater hip external rotation range of motion.[90] It has also been shown that during a squat task, limiting ankle dorsiflexion may induce muscle activation patterns similar to those seen in individuals with patellofemoral pain.[79] In the posterior view, the overhead squat task is used to ascertain excessive pronation, which is predisposing factor for several lower extremity injuries.[89]

The validity of the usage of range of motion of measurements has been extensively investigated, and appears to be a valid way of analyzing some of the causes in individuals' limited movement patterns.[91,92] Range of motion measurements allow for identification of overactive and weak muscles, with areas of particular tightness associated with limitations in certain muscular groups.[89] Identifying tight or overactive musculature indicates what muscles to stretch and lengthen, whereas identifying weak or shortened musculature indicates what muscles to lengthen and strengthen.[89]

Restricted hip and ankle ranges of motion have been associated with most runner's lower extremity injuries.[93] In particular, excessive hip external rotation (greater than 65 degrees) has been evidenced as a predisposing factor for stress fractures.[46] At least 10 degrees of passive ankle dorsiflexion is necessary to decrease potential for injury not only in the ankle but also in other parts of the lower extremity.[52] In particular, this may also include the knee. Knee joints and their associated structures – such as ligaments, capsules, and menisci – are important aspects of force attenuation. During typical impact loading, a joint should move through a particular range of motion – however, if the motion of a joint is restricted, then the loading of the bone is altered. This may result in an increased magnitude of bone strain and consequently perpetuate the formation of stress fractures.[67] Additionally, restricted ankle dorsiflexion with knee extension is associated with Achilles tendonitis.[38] A limitation in the great toe extension range of motion measurement may indicate limited stability in the foot, leading to early supination and a lateral shift of the foot.[88]

While there is a plethora of known predisposing factors predisposing runners to lower extremity overuse injuries, gaps in knowledge exist regarding the accuracy of using preseason movement assessments to predict an elite runner’s lower extremity injuries. Additionally, further research needs to be conducted on how body composition in elite male and female runners affects lower extremity injuries.

CHAPTER III

METHODOLOGY

3.1 – Experimental Design

The purpose of this study was to investigate differences in lower extremity movement patterns and body composition measures between NCAA Division I cross-country athletes who go on to sustain a lower extremity bone stress injury and those who do not. This study employed a prospective cohort methodology. Athletes signed an approved consent form prior to participation. Movement and body composition data were collected at the beginning of the season, and an electronic medical record (EMR) tracked lower extremity stress reactions and stress fractures over the following year.

3.2 – Participants

37 NCAA Division I cross-country athletes (20 males and 17 females) were included in the movement analysis portion this study. 35 NCAA Division I cross-country athletes (19 males and 16 females) were included in the body composition portion of this study. Individuals were divided into a bone stress injury (BSI; males = 2, females = 7; height = 170.82 cm, mass = 57.31 kg, age = 19.67 years) or non-bone stress injury (NBSI; males = 18, females = 10; height = 170.11 cm, mass = 62.73 kg, age = 19.79 years) group, based on if they sustained a lower extremity bone stress injury or not within the year following the preseason testing session.

3.2a – Participant Inclusion Criteria

The study included the 2014-2015 population of male and female cross-country athletes at the University of North Carolina at Chapel Hill. All participants were aged 18 or older.

3.2b – Participant Exclusion Criteria

Individuals were excluded from this study if they were unable to complete functional movement testing due to lack of approval from the team physician or certified athletic trainer. Additionally, individuals who joined the team belatedly and were unavailable for baseline testing were also excluded. One male and one female athlete were excluded for this reason.

3.3 – Instrumentation

3.3a – Dual Energy X-ray Absorptiometry (DEXA)

A DEXA (Hologic Discovery W, Bedford, MA, USA; Apex Software Version 3.3) machine determined the body composition of the participants. The device is a 3 compartment model[94] of body composition. The machine consists of a large, flat table for placement of the participant, as well as an "arm" suspended overhead that performs the scan.[95] The device's flat table alternates producing high and low energy[95] pencil beam[94] X-rays that pass through the participant's body.[95] The "arm" suspended overhead measures the amount of x-rays that pass through the individual to determine body composition.[95] The participant's radiation exposure is minimal,[95] amounting to approximately 0.5μsV per exposure.[96] With standardized methodology and a practiced technician,[96] determining body composition via the DEXA is precise[22,23] and has a 95% agreement with 4 compartment models of body composition measure.[94]

3.3b – Electronic Medical Record (Blue Ocean)

The electronic medical record Blue Ocean (MedStatix, Lancaster, PA, USA) tracked all athlete illnesses and injuries for one year following initial testing. Athletic trainers and physicians entered all injury information based on clinical evaluations and imaging studies.

3.4 – Procedures

3.4a – Protocol

Movement baseline data collection took place one day prior to the start of the cross-country season start. Participants arrived at the Sports Medicine Research Laboratory at the University of North Carolina at Chapel Hill. This research study was a portion of a larger study titled PRIME (Physical Readiness and Integrated Movement Efficiency), which aimed to investigate the effects of lower extremity injury and surgery on hip, knee, ankle, and trunk movement characteristics when matching injured participants to uninjured controls. Participants signed a University Biomedical Institutional Review Board informed consent form that described the procedures and risks identified with partaking in the research project. In addition, they completed a brief verbal questionnaire regarding their history of lower extremity injuries, including surgeries if applicable. Height and mass were measured and recorded. Participants wore their own athletic clothing and were barefoot. Tasks were performed in a randomized order.

3.4b – Movement Assessments

- *Overhead squat*: participants completed 3 sets of 5 repetitions. Participants were instructed to stand with their feet shoulder width apart, toes pointed forward, and arms extended directly overhead. The descent phase of the squat involved the participant going into a flexed knee position as far as he/she was comfortably able, and ascent returned him/her back to the original position. Participants were given a minimum of one practice trial to become comfortable with the task.

Figure 1 – Overhead Squat (Frontal View)

Figure 2 – Overhead Squat (Sagittal View)

- *Single leg squat*: participants completed 3 sets of 5 repetitions on each leg. Participants were instructed to stand on the test foot with toes pointed directly forward. The non-test leg was flexed to 90° at the knee and 45° at the hip. The hands were placed on the hip, with the head and eyes placed forward. The descent phase of the squat involved the participant going into a flexed knee position as far as he/she was comfortably able, and ascent returned him/her back to the original position. Participants were given a minimum of one practice trial on each leg to become comfortable with the task.

Figure 3 – Single Leg Squat (Frontal View)

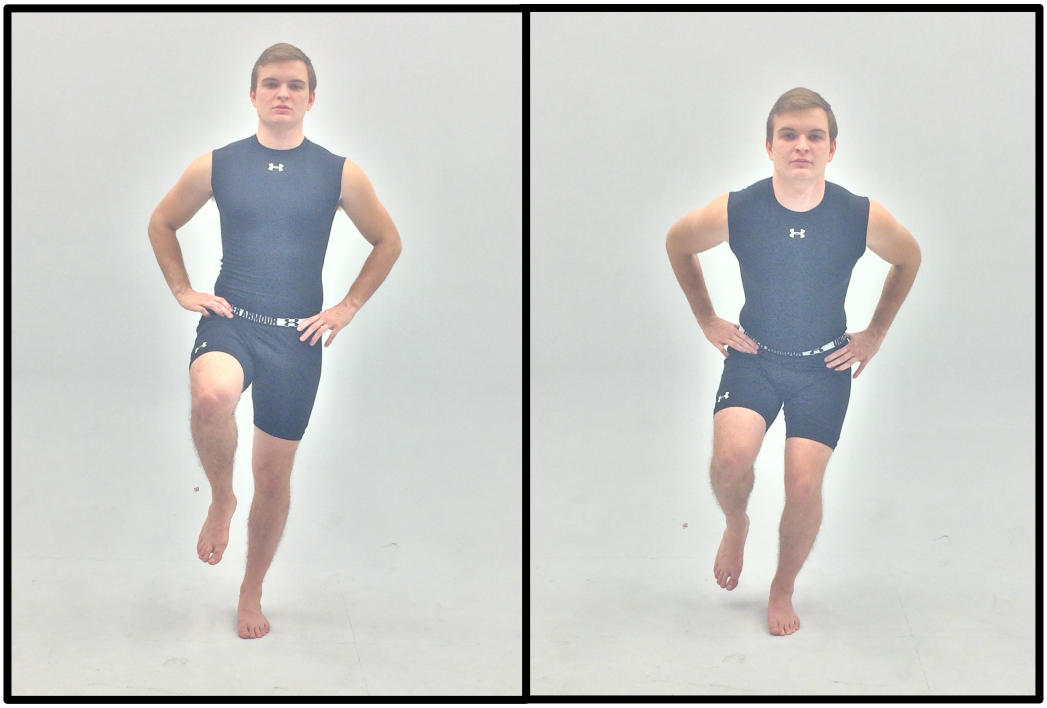
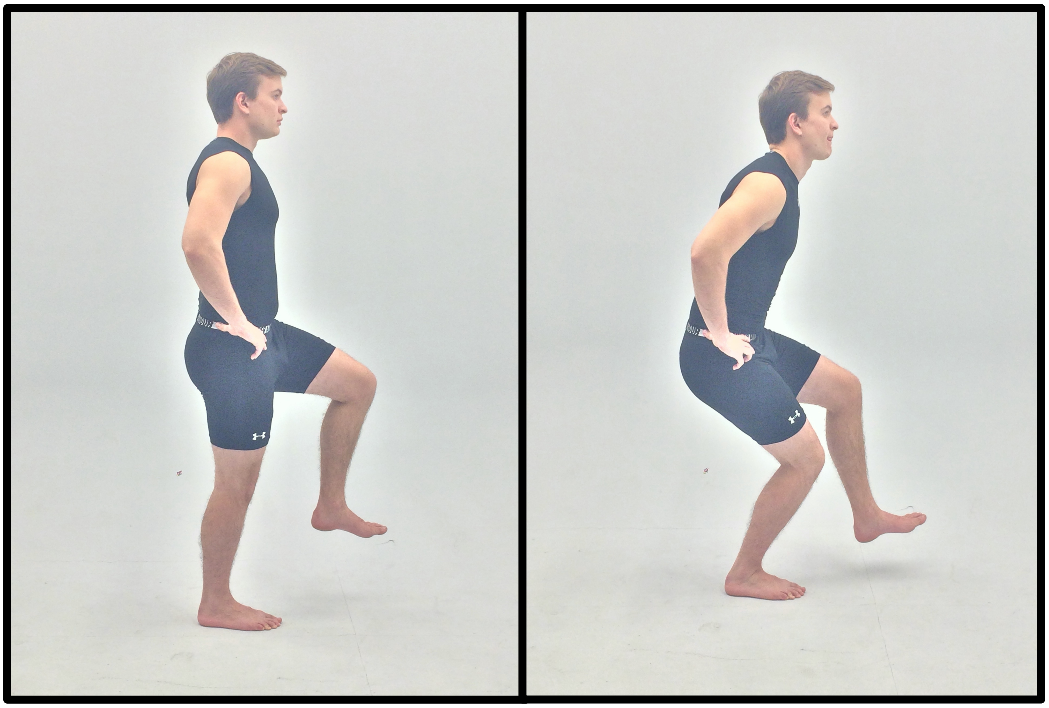


Figure 4 – Single Leg Squat (Sagittal View)



Movement assessments were visually evaluated for movement compensations (errors) by a certified athletic trainer with experience grading clinical movement assessments. The certified athletic trainer's intra-rater reliability for specific movement errors was determined to be between moderate and almost perfect when compared to Fusionetics. Overall, good intra-rater agreement exists for the OHS (kappa = 0.221 - 1; adjusted kappa [PABAK] = 0.12 – 1). This also holds true for the SLS (kappa = 0.257 – 0.779; adjusted kappa [PABAK] = 0.44 – 0.92). Grading for the squats was dichotomous, as either "observed error" or "did not observe error." The athlete was considered to display the particular movement error if the athletic trainer observed the error on at least 3 of the 5 trials.

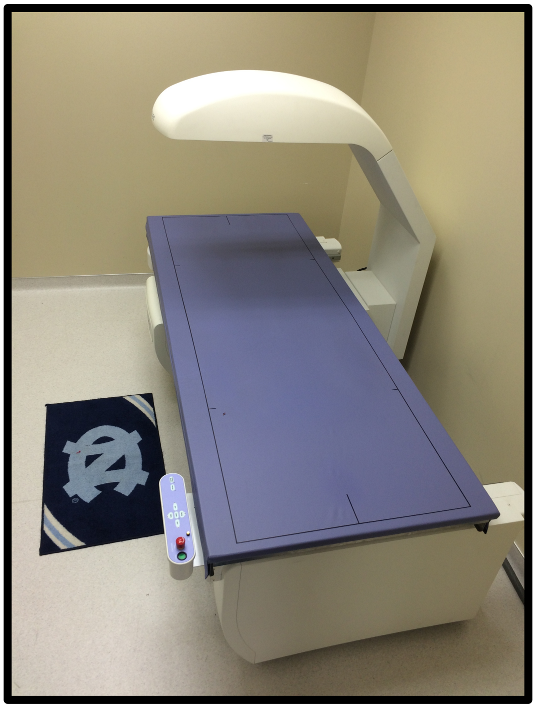
Table 1 – Overhead and Single Leg Squat Errors

Overhead Squat Errors	*Single Leg Squat Errors*
Foot turns out	Foot flattens
Foot flattens	Knee valgus
Knee valgus	Knee varus
Knee varus	Trunk hip shift
Forward lean	Loss of balance
Low back arching	Knee flexion <60^o
Low back rounding	Low back rounding
Arms forward	Trunk flexion rotation
Heel lift	Hip drop or hike
Weight shift	

3.4c – Body Composition

Body composition baseline data collection took place approximately two weeks after the season start. Participants completed a full body DEXA scan.. The athletes wore light clothing and removed metal and heavy plastic for retention of the scan's accuracy. A trained DEXA technician entered information regarding their age, height, weight, sex, and ethnicity into the computer. Participants laid in a supine position in the center of the scanning table with their hands faced palms-down at their sides and were instructed to minimize movement as much as possible. Outcomes of interest for the current study included lean mass (LM), fat mass (FM), body fat percentage (BF%), and bone mineral density (BMD).

Figure 5 – DEXA Machine



3.4d – Injury Tracking

Following pre-season baseline data collection, the participants completed their normal training and competitive seasons. Athletic trainers recorded injuries in an electronic medical record (Blue Ocean) for one year following the initial testing session. The team's athletic trainer was consulted for data regarding athletes who did not have data for 1 full year after follow up. Data were abstracted from the medical record, where the athletic trainer recorded the daily proceedings of the injury, as well as any physician involvement. Participants were dichotomously grouped into two categories, as having sustained a lower extremity stress fracture or bone stress reaction or not having sustained a stress fracture or bone stress reaction within one year of preseason testing. Lower extremity included any body part distal to hips. Stress fractures were confirmed via x-rays, MRI's, and symptomatic differential diagnoses. A stress fracture was defined as an incomplete or complete fracture of the bone stemming from excessive forces acting on the bone.[97] A bone stress reaction left untreated progresses to a stress fracture;[10] both bone stress reactions and stress fractures were included in the search as symptoms and treatment are similar and differentiating between the two diagnoses is challenging.[98] The research team relied on the diagnosis provided by the athletic trainers and physicians.

3.5 – Data Reduction

Data was compiled in a spreadsheet using Microsoft Office Excel (Microsoft Excel 2010; Microsoft Corporation; Redmond, WA). Information regarding each participant's 2014-2015 lower extremity injury status, prior lower extremity injury status, movement, and body composition data were entered. A coding scheme was developed to classify the data in a uniform manner. For the injured leg lean mass comparisons, the lean mass of the injured leg of the injured individuals was compared to the average lean mass of the healthy limbs of all of the uninjured individuals.

3.6 – Data Analysis

Statistical Package for the Social Sciences, version 21 (SPSS, Armonk, NY) analyzed all data. Ten (10) chi-square analyses determined the differences in the proportions of individuals in the bone stress injury and non- bone stress injury groups displaying each overhead squat movement error (foot turns out, foot flattens, knee valgus, knee varus, forward lean, low back arching, low back rounding, arms forward, heel lift, weight shift). Nine (9) additional chi-square analyses determined the differences in the proportions of individuals in the bone stress injury and non-bone stress injury groups displaying each single leg squat movement error (foot flattens, knee valgus, knee varus, trunk hip shift, loss of balance, knee flexion $<60^o$, low back rounding, trunk flexion rotation, hip drop or hike). Independent samples t-tests investigated whether significant differences were present in the means between the bone stress injury and non bone stress injury groups in body composition measures (bone mineral density, fat free mass, and percent body fat) between the bone stress injury and non- bone stress injury groups. Additionally, independent samples t-tests investigated whether significant differences were present in the means between bone stress injury and non bone stress injury groups between injured leg lean mass and the lean mass of lower extremity limbs of uninjured individuals. Values were calculated for equal variances assumed and equal variances not assumed. Significance level was set α of $p \leq 0.05$ a priori.

CHAPTER IV

RESULTS

4.1 – Demographics (Gender, Height, and Age)

There was a total of 10 bone stress injuries identified over the 1-year period, with one of the athletes sustaining more than one injury. Of the 10 injuries, 5 were stress fractures, 4 were stress reactions, and 1 injury was classified as unclear as to whether it was a stress reaction or stress fracture. Stress reactions were located in the tibia, fibula, and metatarsals, while stress fractures were located in the femur, pelvis, tibia, and metatarsals. An overview of the sex of the injured athlete, types of bone stress injury, injury locations and side of the body, as well as the date injury occurred are reported in Table 2.

Females were more likely to sustain a bone stress injury than males (BSI = 77.8%, NBSI = 35.7%; $\chi 2$ (1, N = 37) = 4.85, p = 0.03). When equal variances were assumed, there were no differences between the bone stress injury and non-bone stress injury groups for height (BSI = 170.82 ± 6.87cm, NBSI = 170.11±8.19cm; t(35) = .24, p = 0.815) or age (BSI = 19.67±1.80, NBSI = 19.79±1.52; t(35) = -0.20, p = 0.846). When equal variances were not assumed, there were also no differences between the bone stress injury and non-bone stress injury groups for height (BSI = 170.82 ± 6.87cm, NBSI = 170.11±8.19cm; t(16) = .26, p = 0.799) or age (BSI =

19.67±1.80, NBSI = 19.79±1.52; t(35) = -0.179, p = 0.861). Group statistics for sex, height, and age are reported in Table 3.

Table 2. Bone stress injury overview. Presented according to type of bone stress injury, location of bone stress injury, and days from screening that the injury occurred.

Subject Number	Sex	BSI Type	BSI Location	BSI Body Side	Days From Movement Screening Until Diagnosis
1	Female	Fracture	Tibia	Left	58 days
2	Female	Reaction	4th metatarsal	Right	88 days
3	Female	Reaction	Tibia and Fibula	Right	93 days
4	Female	Fracture	Tibia	Left	116 days
5	Male	Fracture	Pelvis	Left	226 days
6	Female	Reaction/fracture	2nd metatarsal	Right	253 days
7	Male	Reaction	Fibula (proximal and distal)	Right	262 days
8	Female	Fracture	Tibia	Right	272 days
8	Female	Reaction	Tibia	Left	272 days
9	Female	Fracture	Femur	Right	300 days

Table 3. Demographics. Presented as injury counts by genders, and height (cm), mass (kg), and age (years), mean ± standard deviation.

Variable	Bone Stress Injury	Non-Bone Stress Injury	Total
Males	2 (22.2%)	18 (64.3%)	20
Females*	7 (77.8%)	10 (35.7%)	17
Total	9 (100.0%)	28 (100.0%)	37

Variable	Mean ± SD	Mean ± SD	Equal Variances Assumed		Equal Variances Not Assumed	
			P Value	T-Statistic	P Value	T-Statistic
Height	170.82±6.87	170.11±8.19	0.815	0.236	0.799	0.259
Age	19.67±1.80	19.79±1.52	0.846	-0.195	0.861	-0.179

*Indicates a significant difference between groups at p≤0.05.

4.2 – Body Composition Measures

Individuals who went on to sustain a bone stress injury had a lower BMI prior to the start of the season when assuming equal variances (BSI = 19.90±0.70 kg/m^2, NBSI = 21.64±2.32 kg/m^2; t(35) = 2.20, p =0.034) and when not assuming equal variances (BSI = 19.90±0.70 kg/m^2, NBSI = 21.64±2.32 kg/m^2; t(34.98) = 3.51, p =0.001). Injured individuals had a smaller mass when not assuming for equal variances (BSI = 57.31±3.18 kg, NBSI = 62.73±8.41 kg; t(32.56) = 2.77, p = 0.009) but this did not hold true when assuming for equal variances (BSI = 57.31±3.18 kg, NBSI = 62.73±8.41 kg; t(33) = 1.87, p = 0.070). Injured individuals additionally had a significantly smaller lean mass when not assuming equal variances (BSI = 44.03±3.97 kg, NBSI = 49.29±7.93; t(28.20) = 2.58, p =0.015) but not this did not hold true when equal variances were assumed (BSI = 44.03±3.97 kg, NBSI = 49.29±7.93; t(33) = 1.90, p =0.067). There were no differences between the bone stress injury and non-bone stress injury groups for fat mass, percent fat, percent lean mass, or bone mineral density (Table 4).

The leg that went on to sustain a bone stress injury had less lean mass compared to the average lower extremity limbs of the non-bone stress injury group when assuming equal variances (BSI = 4.65±1.72 kg, NBSI = 6.48±0.85 kg; t(32) = 4.13, $p \leq 0.001$) and when not assuming equal variances (BSI = 4.65±1.72 kg, NBSI = 6.48±0.85 kg; t(8.08) = 2.92, p = 0.019). Bone stress injury injured leg lean mass as a percentage of the individual's total mass was significantly smaller when compared to non-bone stress injury group leg lean mass as a percentage of the individual's total mass with equal variances assumed (BSI = 8.25±3.11 kg, NBSI = 10.35±0.32 kg; t(32) = 3.501, p = 0.001) but this did not hold true with equal variances not assumed (BSI = 8.25±3.11 kg, NBSI = 10.35±0.32 kg; t(7.04) = 1.905, p = 0.098). This was also the case when investigating the leg lean mass as a percentage of total lean mass; when equal variances were assumed, the total lean mass of the injured group was smaller than of the uninjured group (BSI = 10.94±4.39 kg, NBSI = 13.24±0.83 kg; t(32) = 2.609, p = 0.014) but this was not the case when equal variances were not assumed (BSI = 10.94±4.39 kg, NBSI = 13.24±0.83 kg; t(7.15) = 1.473, p = 0.183). Injured leg lean mass, injured leg lean mass as a percentage of total mass, and injured leg lean mass as a percentage of total lean mass are reported in Table 5.

Table 4. General body composition measures. BMI, bone mineral density (g/cm^2), mass (kg), fat mass (kg), lean mass (kg), percent fat (%), percent lean mass (%). Presented as mean ± standard deviation.

	Bone Stress Injury	**Non-Bone Stress Injury**	**Equal Variances Assumed**		**Equal Variances Not Assumed**	
Variable	**Mean ± SD**	**Mean ± SD**	**P Value**	**T-Statistic**	**P Value**	**T-Statistic**
BMI*^	19.90±0.70	21.64±2.32	0.034	2.203	0.001	3.514
Mass^	57.31±3.18	62.73±8.41	0.070	1.872	0.009	2.765
Fat mass	10.33±1.78	10.11±1.90	0.771	-0.293	0.767	-0.302
Lean mass^	44.03±3.97	49.29±7.93	0.067	1.896	0.015	2.577
Percent fat	18.38±3.53	16.62±3.49	0.203	-1.299	0.218	-1.291
Percent lean mass	2.18±0.33	2.32±0.40	0.383	0.883	0.346	0.969
Bone mineral density	1.11±0.07	1.13±0.09	0.503	0.677	0.465	0.748

*Indicates a significant difference between groups at p≤0.05 with equal variances assumed.
^Indicates a significant difference between groups at p≤0.05 with equal variances not assumed.

Table 5. Lower extremity specific body composition measures. Injured leg lean mass (kg), injured leg lean mass percent of total mass (%), injured leg lean mass percent of total lean mass (%).

	Bone Stress Injury	**Non-Bone Stress Injury**	**Equal Variances Assumed**		**Equal Variances Not Assumed**	
Variable	**Mean ± SD**	**Mean ± SD**	**P Value**	**T-Statistic**	**P Value**	**T-Statistic**
Injured leg lean mass*^	4.65±1.72	6.48±0.85	≤0.001	4.134	0.019	2.916
Injured leg lean mass percent of total mass*	8.25±3.11	10.35±0.32	0.001	3.501	0.098	1.905
Injured leg lean mass percent of total lean mass*	10.94±4.39	13.24±0.83	0.014	2.609	0.183	1.473

*Indicates a significant difference between groups at p≤0.05 with equal variances assumed.
^Indicates a significant difference between groups at p≤0.05 with equal variances not assumed.

4.3 – Overhead and Single Leg Squats

The bone stress injury and non-bone stress injury groups did not differ in the amount of total errors committed during the overhead squats (BSI = 4.56±2.40 errors, NBSI = 3.86±2.80 errors; t(35) = 0.67 p = 0.506) or single leg squats (BSI = 8.22±3.70 errors, NBSI = 8.32±3.57 errors; t(35) = -0.07, p = 0.943). This information is presented in Table 6. There were no differences between groups for the percentage of individuals who displayed a specific error during the overhead squat (Table 7) or single leg squat (Table 8).

Table 6. Total errors during overhead and single leg squats. Presented as mean ± standard deviation.

	Bone Stress Injury	Non-Bone Stress Injury	
Variable	**Mean ± SD**	**Mean ± SD**	**P-Value**
OHS	4.56±2.40	3.86±2.80	0.506
SLS	8.22±3.70	8.32±3.57	0.943

Table 7. Overhead squat specific errors. Presented as number and percentage of individuals displaying a specific error between bone stress injury and non-bone stress injury groups.

Variable	Bone Stress Injury	Non-Bone Stress Injury	Total	P-Value
Foot turns out	5 (55.6%)	13 (46.4%)	18 (48.6%)	0.634
Foot flattens	2 (22.2%)	9 (32.1%)	11 (29.7%)	0.571
Knee valgus	2 (22.2%)	6 (21.4%)	8 (21.6%)	0.960
Knee varus	4 (44.4%)	5 (17.9%)	9 (24.3%)	0.106
Forward lean	6 (66.7%)	16 (57.1%)	22 (59.4%)	0.613
Low back arching	2 (22.2%)	5 (17.9%)	7 (8.1%)	0.771
Low back rounding	1 (11.1%)	3 (10.7%)	4 (10.8%)	0.973
Arms fall forward	5 (55.6%)	9 (32.1%)	14 (37.8%)	0.208
Heel lift	1 (11.1%)	0 (0%)	1 (2.7%)	0.074
Weight shift	7 (77.8%)	19 (67.9%)	26 (70.3%)	0.571

Table 8. Single leg squat specific errors. Presented as number and percentage of individuals displaying a specific error between bone stress injury and non-bone stress injury groups.

Variable	Bone Stress Injury	Non-Bone Stress Injury	Total	P-Value
Foot flattens	6 (66.7%)	21 (75%)	27 (73.0%)	0.624
Knee valgus	7 (77.8%)	21 (75%)	28 (75.7%)	0.866
Knee varus	0 (0%)	1 (3.6%)	1 (2.7%)	0.565
Trunk hip shift	9 (100%)	27 (96.4%)	36 (97.3%)	0.565
Loss of balance	7 (77.8%)	15 (53.6%)	22 (59.5%)	0.198
Knee flexion <60°	1 (11.1%)	2 (7.1%)	3 (8.1%)	0.704
Low back rounding	0 (0%)	1 (3.6%)	1 (2.7%)	0.565
Trunk flexion rotation	5 (55.6%)	21 (75%)	26 (70.3%)	0.267
Hip drop or hike	6 (66.7%)	19 (67.9%)	25 (67.6%)	0.947

CHAPTER V

DISCUSSION

Nearly 1 in 4 collegiate cross-country athletes sustained a bone stress injury in the present study. Females were more likely to sustain a bone stress injury than males. Pre-season body composition data differed between the bone stress injury and non-bone stress injury groups. Low BMI, low mass, and low lean mass were indicators of bone stress injury development. Leg lean mass in the injured leg was significantly lower when compared to the average mass of the lower extremities of the uninjured group. Surprisingly, lower extremity movement quality did not differ between bone stress injury and non-bone stress injury groups. Thus these findings suggest it may be more important to assess body composition than movement quality when attempting to identify individuals with high potential for developing a bone stress injury.

Previous research regarding the relationship between sex and bone stress injuries is inconclusive. The majority of studies that report females are at greater likelihood for developing a stress fracture,[99-102] and our results verify this with bone stress injuries; however, these findings are not consistent across all studies.[103-105] Furthermore, female distance runners may be the athletic group most likely to sustain a stress fracture.[106] There are a number of sex specific factors that may indicate that females are more likely to sustain a bone stress injury than their male counterparts. These factors include: a wider pelvis and altered loading biomechanics,[107] bones that are less resistant to bending and thus less resistant to injury,[108] higher spongy bone volumetric density that produces more rigid bones,[109] inadequate dairy and calcium intake,[25] and menstrual irregularities[107,110] that may be indicative of an energy imbalance.[25] Diet was not tracked for the participants in this study, but female distance runners who do not have adequate caloric intakes are more prone to energy imbalances that lead to oligomenorrhea and amenorrhea, characteristics that are associated with increased potential for developing a bone stress injury.[105,107,110-112]

Cross-country athletes that sustained a lower extremity bone stress injury had a lower BMI when equal variances were assumed and not assumed. BMI is an indirect measure of body size, correlated with DEXA scan results.[113] It is an indicator of height in relation to weight, but may be inaccurate as it does not discriminate between fat distribution or muscle mass at the same mass.[113] Low BMI has been hypothesized to be indicative of an individual who lacks the adequate total body mass to act protectively against excessive ground reaction forces over the course of a run.[67] Thus, these individuals have a greater likelihood of sustaining lower extremity overuse injuries, including bone stress injuries. The bone stress injury group had a lower mass than the non-bone stress injury group when equal variances were not assumed. Previous research in male military populations has indicated that individuals with a smaller mass are more likely to sustain lower extremity stress fracture injuries.[114] According to the present study, total body mass alone – as compared to mass in relation to height (i.e. BMI measures) – may be a useful indicator of individuals that are likely to sustain a stress fracture injury when used in conjunction with more sensitive measures of body composition (e.g. DEXA data).

This study utilized DEXA data to examine differences between individuals who went on to sustain a bone stress injury and those who did not. DEXA data provided us with the granularity to examine differences in percent fat, percent lean mass, and bone mineral content.[23] Furthermore, with the DEXA data we were able to divide the body into compartments so that the aforementioned variables could be analyzed within body regions of interests, specifically, the lower extremities.[23]

The bone stress injury group had a smaller lean mass than the non-bone stress injury group when equal variances were not assumed. Lean mass refers to the aspects of a runner's body that are used as shock absorbers to offset the excessive ground reaction forces.[35] It is possible that the bone stress injury group had lower extremity muscles that were fatigued, weak, or tight, which would have lessened their ability to attenuate the ground reaction forces,[35] placing more stress on bones and increasing the likelihood of bone stress injury development. It is also possible that these individuals did not have adequate lean mass to act protectively against excessive ground reaction forces traveling up the kinetic chain.

In our study, fat mass and percent fat were not indicators of bone stress injury development. However, other studies have also found amount of fat mass as not indicative of bone stress injury development in female runners.[21,111] BMI is correlated with mass, and as the bone stress injury group in our study had significantly lower BMI it is possible that they lacked excess fat mass. This is especially likely because elite runners are known to have more of their weight as lean tissue as opposed to fat.[75] Thus, the potential exists that fat mass and percent fat were not indicative of this injury development because they were not found in excess and thus did not act detrimentally in our runners.

Low bone mineral density was not an indicator of the development of bone stress injuries. Low bone mineral density reduces the strength of the bone, thus making the bone more susceptible to the accumulation of excess micro damage and stress reaction and stress fracture development.[115] Relationships exist between low bone mineral density and stress fracture development in female athletes.[105,111] However, studies involving only males,[105,116,117] or both males and females,[21] have not found clear relationships between bone mineral density and stress fracture injuries. Running is a repetitive activity that results in bone damage that is typically below the injury threshold. If the bone is given the proper time and nutrients to heal, the strength of the bone will increase.[35] Stronger bones require a greater amount of accumulated damage or a larger single load to overload an elite runner's bone to create a bone stress injury.[9]

The mass of the injured leg was significantly smaller than the averaged mass of the lower limbs of the uninjured group when accounting for both equal variances assumed and equal variances not assumed. This relationship held true when the injured leg lean mass was represented as fractions of the individual's whole mass, or as fractions of the individual's who lean mass with equal variances assumed. It is possible that the bone stress injury group did not have adequate muscle mass in the injured leg and thus were unable to attenuate the ground reaction forces traveling up the kinetic chain,[35] which made them more susceptible to a bone stress injury. Females who sustain stress fractures have less lean mass in the lower limb as compared to the non-stress fracture group.[105] No differences in bone mineral density were observed in this study, thus it is indicative that individuals in the bone stress injury group did not have adequate muscle mass to act protectively against stress fractures.

Overhead and single leg squat movement quality did not differ between groups. Neither the overall numbers of errors nor any specific movement errors differed between individuals who sustained a bone stress injury and those who did not. The overhead squat was chosen for its ability to analyze body alignment[79] and therefore qualitatively assess movement patterns that may contribute lower extremity injury.[89] The single leg squat was chosen as it is a reliable and valid clinical assessment tool[84] for identifying flawed lower extremity movement patterns.[19] Furthermore, as a runner spends 40% of time in the stance phase of movement – with only one foot contacting the ground – the single leg squat is a good representation of the athlete's movement patterns as it also shows the runner's biomechanics during an action with only one foot contacting the ground.[88] However, the overhead and single leg squats may not have been dynamic enough to fully load the joints comparably to ground reaction forces observed during the course of a run. Previous work looking at military cadets identified biomechanical differences between individuals who went on to sustain a stress fracture and those who did not. In this study, Cameron et al.[118] used three-dimensional (3D) motion analysis during a jump-landing assessment to identify biomechanical patterns. Thus, it is possible that in our study, identifying biomechanical errors visually was not a sensitive enough method for identifying differences in movement quality. Additionally, the jump-landing assessment is a more dynamic and demanding task than either the overhead squat or single leg squat, and thus movement errors may be been more pronounced during the jump-landing.[118]

Furthermore our study population only included elite level runners, and it is possible that they have adapted to their aberrant biomechanical patterns and these aberrant biomechanics are not detrimental to the health of the athlete. The specific errors observed during the overhead and single leg squats are biomechanical patterns that have the potential to contribute to bone stress injuries. However, it is typically not any one particular factor but a complex interaction of various intrinsic and extrinsic predisposing factors that produce a bone stress injury.[9] Therefore, it may be challenging to isolate any one particular specific movement flaw as increasing the likelihood of sustaining a bone stress injury.

Several suggestions based on prior research can be made for habit modification in order to limit bone stress injury occurrence. Maximizing bone mass in order to strengthen bones and assuring adequate calcium intake in order to enhance bone mineral density may be beneficial.[119] Optimizing nutrition is also important, as many studies have found an association between disordered eating patterns or inadequate caloric intake and bone stress injury occurrence.[111] Additionally, resistance training and/or Plyometrics are can be utilized to build bone mass and resistance.[119] Early detection of stress reactions before they progress to stress fractures is also of value.[119]

This study had several limitations. The data gathered included both lower extremity stress reactions and lower extremity stress fractures. Although the injuries are similar, hard to differentiate, and the stress fracture is a stress reaction not recognized early enough or left untreated, this may limit the generalizability of the study's findings. Additionally, this may make it challenging to compare the findings of this study to other similar ones. Lower extremity injury data was gathered prospectively via medical records provided by the team's physicians and athletic trainers. Thus, the study relied on information provided by external individuals.

Additionally, the body composition and movement patterns of the athletes may have changed over the course of the season, rendering the preseason assessment less accurate than if the body composition and biomechanical movement data had been obtained directly prior to the injury. However, taking into account that nearly 1 in 4 of the runners sustained a bone stress injury, it is apparent that the body composition and biomechanical factors were still at work. It is also possible that the overhead and single leg squats were not dynamic or challenging enough to load the athlete's body comparably to running. Furthermore, although our observer had great intra-rater reliability when compared to Fusionetics software, visually observing movement errors may not have been sensitive enough of a measure to discern between the bone stress injury and non-bone stress injury groups. Lastly, as the overhead and single leg squats were previously verified to detect differences between healthy and injured subjects in an acute traumatic injury (such as the ACL tear), it is possible that this may have impacted their viability for usage with chronic overuse injuries such as a bone stress injury.

Females were the most injured group of athletes in this study, with 7 out of 17 injured as compared to 2 out of 20 males that were injured. Thus, it is likely that the findings of this study are more indicative of female body composition patterns and female biomechanical patterns.

Based on the results and implications of this study, there are several suggested directions for future research. Firstly, the methods of this study should be replicated with novice runners as they may have a greater chance of sustaining a bone stress injury .[120] This will allow the findings of the present study to be more generalizable to the general athletic population. Another suggestion is to incorporate movement assessments that are more dynamic in nature, as they may be better predictors of the dynamic movement patterns exhibited by an athlete over the course of a run. An example of such a dynamic movement assessment is the jump-landing task and the Landing Error Scoring System. This method of biomechanical analysis has previously been proven to be a reliable clinical assessment tool for easy implementation.[121] Additionally, it may be useful to look at bone mineral density at bone stress injury specific sites,[111] as this association may prove to be a more accurate indicator of bone mineral density for a bone stress injury injured athlete. Lastly, it may be beneficial to look at specific muscle characteristics, such as muscle cross sectional area, at stress specific lower extremity sites. This will allow for analysis of muscle size and quality, characteristics that when bettered may improve functionality and decrease potential for lower extremity injury.[21]

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