

USING A BEAM THEORY MODEL TO QUANTIFY METATARSAL
BONE STRESS DURING RUNNING

by

Kaitlyn Marie McKibben

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Exercise Physiology and Nutrition

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2023

©COPYRIGHT

by

Kaitlyn Marie McKibben

2023

All Rights Reserved

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Jim Becker, and committee members, Dr. Scott Monfort and Dr. John Seifert, for providing your time, guidance, and knowledge. I have learned so much from all of you over the past two years.

To my family and friends, thank you for your endless love and patience. I am so grateful for the support and encouragement you have given me throughout this process and that you give me always.

Lastly, I would like to thank all the other graduate students who have become friends over the past two years. Meeting all of you has made this experience more enjoyable than I ever could have thought. To Leah and Megan, thank you for all the support and for keeping me laughing through it all. I could not imagine doing this without you.

TABLE OF CONTENTS

1. INTRODUCTION	1
References	4
2. REVIEW OF RELATED LITERATURE	6
Running and Injury Incidence	6
Metatarsal Bones	7
Stress Fracture Etiology and Bone Stress	8
Stress Fracture Risk Factors	10
Anatomical Risk Factors	10
Physiological Risk Factors	11
Extrinsic and Biomechanical Risk Factors	12
Methods of Measuring Bone Stress	13
In Vivo Direct Measurements	13
Cadaver Models	15
Finite Element Analysis	15
Beam Theory Model	16
Measuring Bone Stress in a Clinical Setting	19
Metatarsal Stress During Running	20
Metatarsal Stress and Long Distance Running	21
Summary	22
References	24
3. ACUTE EFFECTS OF A NON-EXHAUSTIVE LONG RUN ON METATARSAL BONE LOADS	30
Contribution of Authors and Co-Authors	30
Manuscript Information	31
Abstract	33
Introduction	34
Methods	36
Participants	36
Protocol	36
Data Analysis	38
Statistical Analysis	39
Results	39
Discussion	46
Conclusion	53
References	54

TABLE OF CONTENTS CONTINUED

4. THIRD METATARSAL HEAD AND BASE PRESSURE DIFFERENTIALS PREDICT BONE STRESS IN COLLEGIATE CROSS-COUNTRY RUNNERS.....	58
Contribution of Authors and Co-Authors	58
Manuscript Information	59
Abstract	61
Introduction.....	62
Methods.....	64
Participants.....	64
Protocol.....	64
Data Analysis.....	66
Statistical Analysis.....	67
Results.....	67
Discussion.....	68
Conclusion	72
References.....	74
5. DISCUSSION AND CONSLUSIONS.....	77
References.....	82
REFERENCES CITED.....	83

LIST OF TABLES

Table	Page
CHAPTER THREE	
1. Vertical Ground Reaction Force Beneath the Metatarsal Heads	40
2. Time of Peak Stresses and Bending Moments.....	46
CHAPTER FOUR	
1. Peak Model Input Values.....	68
2. Regression Model Statistics	68

LIST OF FIGURES

Figure	Page
CHAPTER TWO	
1. Metatarsal Bones.....	7
2. Hill's (1998) depiction of the bone remodeling cycle	9
3. Injury Threshold Curve.....	10
4. Mathematical model of the metatarsals	17
CHAPTER THREE	
1. Peak Metatarsal Stress and Bending Moment Values	41
2. Metatarsal Stress and Bending Moments Across Time	43
3. Vertical Ground Reaction Forces Under the Metatarsal Heads.....	52
CHAPTER FOUR	
1. Force Plate and Plantar Pressure Mat	65

ABSTRACT

Running is a common fitness activity that is associated with a high incidence of overuse injuries, including metatarsal stress fractures. One contributor to stress injury is repetitive loading of the metatarsals without adequate recovery time and experiencing larger volumes and magnitudes of bone loading may increase injury risk. Thus, quantifying metatarsal loads can be beneficial to understanding injury risk. However, it is currently difficult to estimate bone stress in clinical settings and unclear how bone stress changes following a long run. Therefore, the purpose of this thesis was to 1) characterize changes in metatarsal bone stress before and after the completion of a long-distance run, and 2) suggest a clinically feasible method for estimating metatarsal bone stress. Study 1 involved 21 healthy long-distance runners who ran 25% of their average weekly mileage on an instrumented treadmill. Foot kinematics, ground reaction forces, and in-shoe plantar pressures were collected at the beginning and end of the run and a mathematical model was used to estimate bone stresses and bending moments for all five metatarsals. Plantar stress, dorsal stress, and midshaft bending moments in the second and third metatarsals were greater after the completion of the run. This is consequential for injury risk because the second and third metatarsals are the most susceptible to stress fracture development. In study 2, seventeen runners ran barefoot across a force plate overlaid with a plantar pressure mat while foot kinematics were recorded. The same mathematical model of the metatarsals was used to estimate third metatarsal bone stresses and bending moments, and linear regressions determined whether force or pressure beneath the metatarsal predicted bone loads. A model containing head and base pressure differentials and force beneath the metatarsal head was the best predictor of bone loading, indicating that the use of plantar pressure measurements as a surrogate measure of bone stress could be a time and cost-effective method for estimating bone stress in clinical settings. Moving forward, elucidating how metatarsal bone stress changes over the course of a long run and finding more accessible ways to quantify bone stress could help alleviate injury risk.

CHAPTER ONE

INTRODUCTION

Running is a popular activity that is enjoyed by people all over the world. Despite numerous health benefits, running is also associated with a high incidence of overuse injuries. In any given year, over half of runners will experience some sort of running-related injury. Given the repetitive nature of the activity, these injuries are more often a result of overuse rather than acute incidents. The majority of running related overuse injuries affect the lower extremity and of these injuries, 16% will be stress fractures.¹ Additionally, 9% will occur in the metatarsal bones and the vast majority will happen in the second and third metatarsals.² Stress fracture development is multifactorial, but the main mechanism of injury is repetitive loading. Large loading volumes of sizeable magnitudes, combined with a lack of rest time for bone to recover, can result in stress fracture injury.

Long-distance runners are especially susceptible to these injuries. Injury incidence in distance runners has been estimated to be as high as 79% per year and those who run more than 20 miles per week are at a higher risk.^{3,4} Greater mileage allows for increased overloading of the tissues and more opportunity for injuries like stress fractures. Given the increase in injury rate, it is important to know how bone stress changes after a long run to further our understanding of possible injury risk. While previous studies have looked at the effects of footwear and foot strike on metatarsal bone stress,^{5,6} there is an absence of literature looking at metatarsal loading after a long-distance run. Instead, most current studies looking at changes in loading patterns after a long run have focused on force and pressure measurement beneath the foot.⁷⁻⁹ Most of these previous studies agree on how external loading changes following a long run. Compared to pre

run conditions, force and pressure measurements following a long run show increased loading beneath the metatarsal heads and a decrease in loading beneath the toes. This is most likely a result of fatigue in the plantar flexors, causing the toes to be less effective in propelling the foot forward and instead transferring more load under the forefoot region.⁷ Many of these studies have suggested that an increase in external loading will be accompanied by an increase in internal loading of the metatarsals. However, other studies have suggested that ground reaction forces and plantar pressure measurements are not indicative of internal bending moments and stresses.^{6,10} Given these discrepancies, it remains unclear how metatarsal bending moments and stresses change after the completion of a long run.

Although having a better understanding of internal loading could help to alleviate injury risk, bone stress is difficult to measure. Directly measuring bone stress can be invasive and costly, requiring surgical implantation of strain gauges and staples, or the use of cadaver specimens.¹¹ Indirect measurements using mathematical models are less invasive, but still time and resource intensive.^{6,12} Modeling can require precise motion capture and force measurements, the equipment for which is expensive and typically not available in most clinical settings. However, previous literature has suggested that the difference in pressure between the head and base of the fifth metatarsal may be a useful surrogate measure for bending moment, and as an extension, compressive and tensile stresses acting on the shaft of the metatarsal.¹³ If pressure differentials are in fact predictive of internal bone loading this could potentially present a method of estimating metatarsal bone stress that is clinically feasible. Plantar pressure mats are inexpensive and easy to use in comparison to other methods of measuring and estimating bone stress. A patient would simply need to run across the mat and pressure measurements can be

quickly analyzed, potentially removing barriers so that stress can be estimated in clinic and potential injury risk can be more easily identified.

The lack of knowledge regarding how metatarsal bone loads change and the absence of a quick and easy method of estimating internal loads should be remedied to better understand and prevent injury risk. Therefore, the purpose of the following thesis was to assess metatarsal bone stress in two different conditions. Chapter Two contains a review of the literature associated with metatarsal bone stress during running, providing a background for subsequent research. Chapters Three and Four will include manuscripts addressing two separate research questions:

Research Question 1

There is a lack of consensus regarding how metatarsal bone stress changes after the completion of a long-distance run. Study 1 will attempt to characterize changes in metatarsal stress before and after the completion of a non-exhaustive run equivalent to 25% of a runner's average weekly mileage. We hypothesize that plantar stress, dorsal stress, and bending moment values will be greater at the completion of the run.

Research Question 2:

A clinically feasible method of estimating metatarsal bone stress could be beneficial in determining if a runner is at risk of a bone stress injury. However, current methods are not feasible for in-clinic use. Study 2 will examine whether measures of external loading are predictive of metatarsal stresses. It was hypothesized that a greater difference in pressure between the head and base of the third metatarsal would predict greater peak values of plantar stress, dorsal stress, and midshaft bending moments.

References

1. Mayer SW, Joyner PW, Almekinders LC, Parekh SG. Stress Fractures of the Foot and Ankle in Athletes. *Sports Health*. 2014;6(6):481-491. doi:10.1177/1941738113486588
2. Chuckpaiwong B, Cook C, Pietrobon R, Nunley JA. Second metatarsal stress fracture in sport: Comparative risk factors between proximal and non-proximal locations. *Br J Sports Med*. 2007;41(8):510-514. doi:10.1136/bjsm.2006.033571
3. Hootman J, Macera C, Ainsworth B, Martin M, Addy C, Blair S. Predictors of lower extremity injury among recreationally active adults. *Clin J Sport Med*. 2002;12(2):99-106.
4. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Br J Sports Med*. 2007;41(8):469-480. doi:10.1136/bjsm.2006.033548
5. Firminger CR, Fung A, Loundagin LL, Edwards WB. Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics*. 2017;49:8-15. doi:10.1016/j.clinbiomech.2017.08.006
6. Ellison MA, Kenny M, Fulford J, Javadi A, Rice HM. Incorporating subject-specific geometry to compare metatarsal stress during running with different foot strike patterns. *J Biomech*. 2020;105. doi:10.1016/j.jbiomech.2020.109792
7. Nagel A, Fernholz F, Kibele C, Rosenbaum D. Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait Posture*. 2008;27(1):152-155. doi:10.1016/j.gaitpost.2006.12.012
8. Willems TM, De Ridder R, Roosen P. The effect of a long-distance run on plantar pressure distribution during running. *Gait Posture*. 2012;35(3):405-409. doi:10.1016/j.gaitpost.2011.10.362
9. Alfuth M, Rosenbaum D. Long distance running and acute effects on plantar foot sensitivity and plantar foot loading. *Neurosci Lett*. 2011;503(1):58-62. doi:10.1016/j.neulet.2011.08.010
10. Matijevich ES, Branscombe LM, Scott LR, Zelik KE. Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. *PLoS One*. 2019;14(1). doi:10.1371/journal.pone.0210000
11. Arndt A, Ekenman I, Westblad P, Lundberg A. *Effects of Fatigue and Load Variation on Metatarsal Deformation Measured in Vivo during Barefoot Walking*. Vol 35.; 2002.

12. Gu YD, Ren XJ, Li JS, Lake MJ, Zhang QY, Zeng YJ. Computer simulation of stress distribution in the metatarsals at different inversion landing angles using the finite element method. *Int Orthop*. 2010;34(5):669-676. doi:10.1007/s00264-009-0856-4
13. Orendurff MS, Rohr ES, Segal AD, Medley JW, Green JR, Kadel NJ. Biomechanical analysis of stresses to the fifth metatarsal bone during sports maneuvers: Implications for fifth metatarsal fractures. *Physician and Sportsmedicine*. 2009;37(2):87-92. doi:10.3810/psm.2009.06.1714

CHAPTER TWO

REVIEW OF RELATED LITERATURE

Running and Injury Incidence

Running is a popular activity enjoyed by people of all ages. In the United States, somewhere between 40 to 60 million people regularly participate in running activities.^{1,2} Reasons for participation can include competitive sport, leisure, or general health and fitness.³ Running is associated with numerous physical and mental health benefits including improved cardiovascular health and overall longevity.^{4,5} However, running is also associated with a high incidence of overuse injury. Nearly half of all runners will experience a running related injury in a given year.⁶ Long-distance running can be especially burdensome with up to 79% of long-distance runners injured each year.⁷ The majority of running related injuries affect the lower extremity and of these injuries, 16% will be stress fractures.⁸ In particular, metatarsal stress fractures make up almost 9% of all running injuries,⁹ with 80-90% occurring in the second and third metatarsals.¹⁰ Stress fractures most often manifest as localized or “pinpoint” pain that increases with activity.¹¹ Depending on the severity of injury, a person who has sustained a stress fracture could spend anywhere from 2-12 weeks non-weight bearing or in a walking boot and need physical therapy¹². Not only can healthcare costs and lost training time be detrimental for an individual, but previous stress fracture injury is a significant risk factor for future stress fracture injury.¹³

Metatarsal Bones

The metatarsals are the long bones of the foot (Figure 1). Along with the tarsal bones, they help form the arch of the foot, providing structure and support and aiding in absorption and redistribution of forces. Additionally, the metatarsals act as origin and insertion points for many leg and foot muscles and act as the main weight bearing region of the forefoot.¹⁴ The foot consists of three different arches. The first, second, and third metatarsals, along with the cuneiform bones, navicular bone, and calcaneus, form the medial longitudinal arch. This arch is flexible and is the location of arch height measurement, a determinant of arch type and many foot-related pathologies.¹⁵ The lateral longitudinal arch is formed by the fourth and fifth metatarsals, cuboid, and calcaneus. This part of the longitudinal arch lies closer to the ground and is less flexible than the lateral portion.¹⁶ The bases of all five metatarsals help to make up the transverse arch. All three arches work together to quickly adapt to changes in terrain.

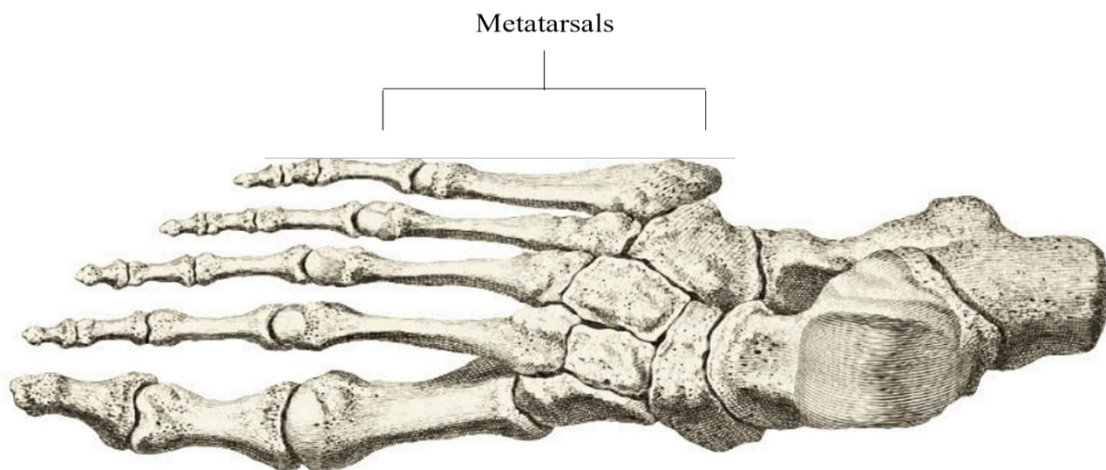


Figure 1. Metatarsal Bones. (Public domain image. Labels added.)

The first metatarsal is the shortest and thickest of the five bones and is typically subjected to the largest loads. The remaining four metatarsals are longer and much slimmer, with the second metatarsal being the longest. The first and fifth metatarsals are flexible, with a range of motion allowing them to move and adapt as the foot encounters uneven surface. The second, third, and fourth metatarsals are less flexible, instead acting more like rigid beams. Compared to the first and third metatarsals, the second metatarsal base is set more proximally in the foot. This allows the second metatarsal to lock into place with the middle cuneiform bone and become especially rigid during the propulsive phase of normal gait (the latter part of stance phase when weight is shifted to the front of the foot and forces begin to push the body forward). In this configuration, the second metatarsal can provide stability to the forefoot and transmit additional forces.¹⁴ However, less flexibility through the shaft makes the middle metatarsals more susceptible injury from bending stresses.⁹

Stress Fracture Etiology and Bone Stress

Stress fractures develop in response to repeated submaximal loading combined with a lack of proper recovery time.¹⁷ Loads applied to bone cause deformation which can result in microfractures, even at submaximal loads, while even further loading leads to decreased material stiffness and increased strain.¹⁷ Bone is a biologically active material that can act in response to mechanical loading demands. Microdamage, as a result of loading, is repaired through the bone remodeling cycle.¹⁸ When bone experiences stress induced microfractures, osteoclasts remove the damaged bone and osteoblasts lay down new cells, often leading to an increase in bone strength in that area (Figure 2).¹⁹ Bone is temporarily weakened during this cycle before being repaired and becoming stronger. However, this cycle does not always have time to complete.

Repetitive submaximal loading that occurs too quickly without proper recovery time for the cycle to complete can lead to material failure, causing injuries such as stress fractures.¹⁷

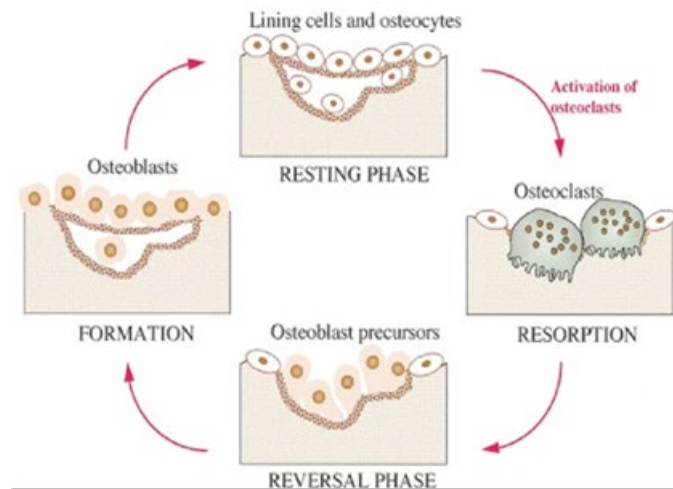


Figure 2. A depiction of the bone remodeling cycle.¹⁹

The theoretical amount of repetitive loading that can be endured before failure is highly dependent on the injury threshold of the material (Figure 3). The actual amount of loading that can be endured is dependent on material properties and the amount of load being placed on the structure. Stress fractures most often occur within cortical bone.²⁰ Cortical bone is compact and dense, forming the protective outer layer of bone. It is made of collagen fibers organized into a lamellar structure and less metabolically active than trabecular bone.²¹ While it can be hard to identify an exact yield point for cortical bone, cortical bone is stronger in compression than in tension and a yield strain ratio between compression and tension has been previously suggested.²² When cortical bone is in tension, fractures happen very quickly once the ultimate yield point is passed.

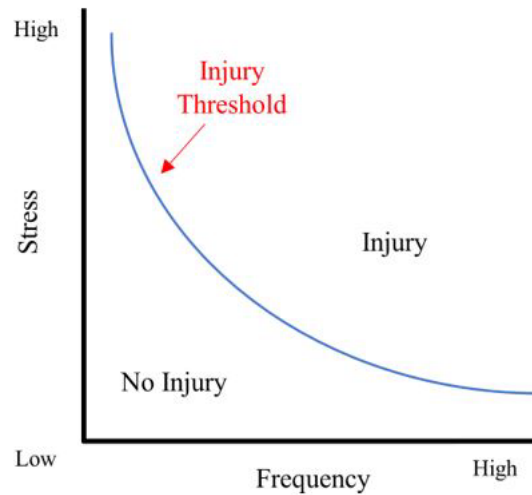


Figure 3. A theoretical injury threshold for overuse injuries. The frequency of load and the magnitude of stress will determine whether there is risk of injury or not. Image adapted from Ferber et al.⁷³

Stress Fracture Risk Factors

Stress fractures are increasingly common injuries in the general population, and even more so in athletic populations. Up to 20% of visits to sports medicine doctors are concerning stress fractures.²³ Despite their prevalence, the exact cause of stress fracture injuries can be difficult to pinpoint. The origin of most stress fractures is multifactorial, and a number of risk factors have been discussed in the literature. While most stress fractures arise from multiple causes, development can be related to anatomy, physiology, and biomechanical factors.⁹

Anatomical Risk Factors

Certain anatomical characteristics of the foot are considered risk factors for increased stress fracture risk. Anatomical risk factors are attributes that are typically nonmodifiable without intervention and contribute to injury risk by changing how forces are transmitted through the foot. Both pes planus, commonly known as flat foot deformity, and pes cavus, a high arch

deformity, have been shown to increase metatarsal stress fracture risk. Exhibiting increased hindfoot eversion or forefoot varus during normal stance have also been identified as risk factors.²⁴ Metatarsal adductus, where the distal ends of the metatarsal bones deviate inwards, can also influence injury risk because of how the deformity causes loads to distribute across the foot.²⁵ Discrepancies in leg length have also been identified as risk factors for unilateral stress fracture risk.⁹ Lack of joint range of motion and tight muscles can also increase injury risk, although these anatomical risk factors are potentially modifiable. Having low bone mineral density (BMD) affect the strength of bones and the amount of forces bones can withstand before reaching a point of failure.¹³ Low BMD is often categorized as an anatomical risk factor because it affects the mechanical properties of bone but is often caused by physiological traits as discussed below.

Physiological Risk Factors

Physiological risk factors for stress fracture often relate to internal processes and nutrient availability. Bone remodeling that happens either too quickly or too slowly have been suggested as risk factors. A fast-remodeling cycle means that damaged bone may be absorbed before new bone is formed, while a slow remodeling cycle would not be able to keep up with the bone maintenance required to prevent injury during normal loading. Studies have shown that those who develop stress fracture have elevated biomarkers suggesting increased bone turnover, although this has not been established as a reliable method of determining bone remodeling rate.¹³

Sex is a risk factor for stress fracture, with the injury being more common in females.²⁶ Low BMD is more often seen in females, and along with low energy availability and

amenorrhea, make up the female athlete triad.²⁷ Exhibiting any of the three components of the triad significantly increases chances of developing a stress fracture. Low body mass index and increasing age are also risk factors, most likely due to lack of nutrients and decreases in estrogen levels.²⁶ Additionally, having a prior stress fracture is a risk factor for women. In one study, female runners with prior stress fracture were six times more likely to develop a subsequent stress fracture compared to those who had not had a stress injury.²⁸

Lack of nutrients are contributors to risk of stress fracture development. Studies have suggested that adequate intake of both vitamin D and calcium are associated with a decreased injury risk, potentially because these nutrients are associated with adequate BMD.⁹ Additionally, women who had previously had an eating disorder were five time more likely to develop a stress fracture, indicating the importance of proper nutrition in stress fracture prevention.²⁹

Extrinsic and Biomechanical Risk Factors

Extrinsic stress fracture risk in runners mainly includes training conditions. Running on hard surfaces, such as concrete, may increase risk. However, running on softer surface can cause muscle fatigue more quickly, which could affect load distribution.¹³ Footwear choice is also influential. Military recruits are more susceptible to third metatarsal stress fractures when training in combat boots rather than running shoes potentially due to increased ankle stiffness in the combat boot.³⁰ Different running shoes have been shown to have different center of pressure trajectories and pressure distributions and traditional shoes have decreased peak pressures compared to minimalist shoes.³¹ Similarly, the use of insoles can alter loading parameters and influence stress fracture risk.¹³ Changes in training program that increase bone loading, such as a sudden increase in mileage, can be detrimental for injury risk. In fact, over 80% of surveyed

athletes that were recovering from a stress fracture identified either an increase in intensity or a new training protocol in the time directly before their injury.¹³ Larger weekly mileages have also been identified as a risk, with people running over 20 miles per week at a greater risk of suffering a lower extremity over use injury.³² Finally, running gait abnormalities can increase the likelihood of experiencing a stress fracture. Characteristics of running gait such as increased peak rearfoot eversion, contralateral pelvic drop, and increased knee internal rotation during the flight phase have all been suggested as potential contributing factors to stress fracture risk.^{13,33} Abnormal loading can also be an issue and increased vertical loading rate is thought to be a risk factor for stress injuries. Running gait abnormalities can often be identified during a running gait analysis and remedied to prevent stress fractures or other overuse injuries.

Methods of Measuring Bone Stress

Calculating bone stress can be done in a myriad of different ways but can be summarized into two main categories: indirect and direct measurements. Direct measurements include in vivo and in vitro testing using either live human participants or cadaver bones. These methods are highly invasive and generally difficult to perform,³⁴ but offer the most accurate depiction of bone loading.³⁵ Indirect measurement utilizes mathematical models that incorporate techniques such as finite element analysis and models based off beam theory. While not invasive, mathematical models require simplifications that may affect the accuracy of bone loading estimates.³⁵

In Vivo Direct Measurements

In vivo direct measurements are the gold standard of calculating bone stress.³⁵ Most commonly, these require surgical implantation of a strain gauge directly into the bone and

application of a substance to adhere the device. The gauge then measures changes in resistance when forces are applied to the bone, either causing contraction or elongation of the tissue.³⁶ Of the four current studies that have performed in vivo measurements on the foot, three took place in the second metatarsal.³⁷⁻³⁹ When looking at walking, jogging, and jumping, Milgrom et al. found that compressive strains in the second metatarsal were greater than in the medial tibia and that measured metatarsal compressive and tensile strains were within normal ranges for physiological loading, except for tensile strain during jumping, which was categorized as overloading the tissue.³⁹ Arndt et al., found increased compressive strain was seen when walking barefoot with a weighted backpack and in a fatigued state, compared to without weight and in an unfatigued state.³⁷ The same authors found that different shoe conditions changed dorsal tensile strains during walking.³⁸

Despite being the gold standard for bone stress measurement, in vivo strain gauge techniques have many drawbacks, the largest being that this method requires a surgical operation to implant the measurement device directly into the bone. Not only is this highly invasive, but it is also difficult to recruit participants and due to time and resources, cannot feasibly be used in studies with large numbers of subjects. Current studies using this method all involve 10 participants or less.⁴⁰ Further, use of surgical implantation of devices can only be done on easily accessible, superficial bones, making this impractical for testing on the majority of human bones. The three strain gauge studies mentioned above only measured strains on the dorsal side of the second metatarsal due to the impossibility of implanting a device on the plantar side of the bone.³⁷⁻³⁹ As of 2012, in vivo bone stress measurements had only been performed on seven bones in the body.³⁵

Cadaver Models

Cadaver specimens are often used for investigating causes of illness and practicing surgical techniques but can be used to test mechanical properties of various tissues, including bone.⁴¹ Cadaver specimens have been used to determine point of material failure and location of failure in the metatarsals.⁴² Use of cadaver feet have also been used to measure metatarsal stress under dynamic scenarios. Walking performed with a gait simulator has shown that cadaveric second metatarsals equipped with strain gauges have much larger peak strains than fifth metatarsals, and second metatarsal strain increases significantly with the introduction of simulated muscle fatigue.⁴³ Similar methods that are used in vivo can be used on cadaver bones but are much less invasive than when used on a live participant. However, bone is not an isolated tissue and removing a bone from its environment can eliminate the effects that surrounding tissues have on the mechanical properties of bone.

Finite Element Analysis

One common method of indirect stress measurement is finite element (FE) analysis. Finite element analysis is used to model objects or materials under a set of conditions using mathematical equations to predict the response of that object. This method has been used to model behavior of bone since the 1970's.⁴⁴ Unlike the use of in vivo methods that measure strain at a specific spot, FE models can simulate stress distribution across a bone, as well as the effects of surrounding tissues, which gives more useful information about the effects of external loading on the bone as a whole. Finite element analysis has been used in numerous studies to determine the response of the metatarsals to injury. When looking at patients with hallux valgus (a condition where the first phalanx deviates laterally while the 1st metatarsal deviates medially) FE

models show increased concentrations of stress in the metatarsals of pathological patients compared to those without the deformity.⁴⁵ In another study, foot shape and posture were analyzed in patients recovering from fifth metatarsal stress fractures. It was found that eversion and dorsiflexion of the foot caused greater strains within the fracture compared to normal stance.⁴⁶ Additionally, FE analysis has been used to look at metatarsal stresses during walking and running. When running in minimalist style footwear, FE models have shown that increases in stress in the metatarsals corresponds with increases in external loads, and that the metatarsals are more than capable of withstanding loads 2.5 times body weight underneath the metatarsal area.⁴⁷ Finite element analysis does have downsides as it can be computationally costly and in order to develop FE models, thorough imaging needs to be performed to understand the geometry of the desired object. With bone, this is typically done using computer tomography (CT), magnetic resonance imaging (MRI), or bone mineral density (BMD) scans, which can be expensive to perform.⁴⁴ Because of this, many studies using FE analysis have a small sample size.

Beam Theory Model

In 1979, Stokes et al. proposed a mathematical model of the metatarsals based on beam theory in an effort to relate the external forces acting on the metatarsals with the internal loads experienced by the metatarsals.⁴⁸ The metatarsal bones are modelled as hollow ellipses and beam theory is used to explain behavior of the bone in response to bending loads.⁴⁹ Calculated stresses act at a single point at the midpoint of the metatarsal shaft. Many studies have used beam theory to model long bones as a less computationally exhaustive alternative to FE analysis.^{50,51} The use of beam theory to model the metatarsals makes many assumptions including simplifying the

geometry of the metatarsal bones making it less accurate than other modeling techniques and sometimes prone to overprediction of dependent variables.^{52,53} Despite this, beam theory has been suggested as an appropriate method of estimating bone stresses when comparing relative values between conditions.^{51,54}

The model first proposed by Stokes et al. was used to calculate axial forces, shear forces, and bending moments during barefoot walking gait.⁴⁸ Building off this model, Gross & Bunch calculated similar variables during shod running.⁵⁵ Finally, Ellison et al. adapted the model to calculate compressive stress, tensile stress, and midshaft bending moments of the third metatarsal during barefoot running (Figure 3).⁵⁴ This was the first model of the metatarsals based on beam theory to incorporate subject-specific geometry in an effort to account for the non-homogeneity of the metatarsal.

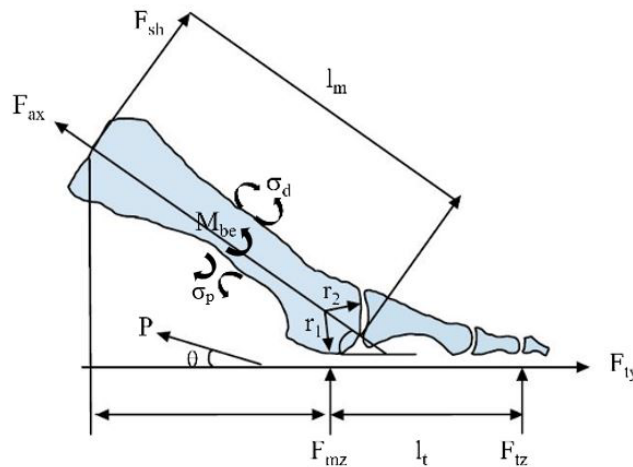


Figure 4. A mathematical model of the metatarsals based on beam theory that can be used to find stresses and bending moments acting at the midpoint of the metatarsal shaft. Adapted from Ellison et al. (2020).⁵⁴

While incorporating components from each iteration of the model, the current work mainly uses the equations and assumptions made by Ellison and colleagues, described here.⁵⁴

The lower radius of the metatarsal head (r_1), length of the toe (l_t), ground reaction forces beneath the toe in the vertical direction (F_{tz}), and the distance from the bottom of the metatarsal head to the attachment site of the plantar tendon (ε) are used to calculate the force from the plantar tendon (P):

$$F_{tz}l_t = P(\varepsilon + r_1)$$

Ground reaction forces beneath the toe are then used to calculate joint reaction forces at the metatarsophalangeal joint (F_j):

$$F_t + F_j + P\sin\theta = 0$$

where θ is the angle of the plantar tendon relative to horizontal. Axial (F_{ax}) and shear (F_{sh}) forces acting on the metatarsal shaft are then calculated using the joint reaction force at the metatarsophalangeal joint and ground reaction forces acting beneath the head of the metatarsal (F_m) in the anterior-posterior (y) and vertical (z) directions:

$$F_{ax} = F_{mz}\sin\alpha - F_{my}\cos\alpha + F_{jy}\cos\alpha - F_{jz}\sin\alpha$$

$$F_{sh} = F_{mz}\cos\alpha + F_{my}\sin\alpha - F_{jz}\cos\alpha - F_{jy}\sin\alpha$$

Midshaft bending moments (M_{be}) were then calculated using:

$$M_{be} = \left(\frac{l_m - r_2}{2}\right)(F_{mz}\cos\alpha + F_{my}\sin\alpha - F_{jz}\cos\alpha - F_{jy}\sin\alpha)$$

where l_m is the length of the metatarsal, r_2 is the upper radius of the metatarsal head, F_m is the force beneath the metatarsal head, F_j is the joint reaction force at the metatarsophalangeal joint, and α is the angle between the metatarsal and the floor. From here, axial stress (σ_{ax}) and bending stress (σ_{be}) can be solved for:

$$\sigma_{ax} = \frac{F_{ax}}{CSA} \quad \sigma_{be} = \frac{M_{be}r}{I}$$

where CSA is the cross-sectional area of the midpoint of the metatarsal shaft, and I is the moment of inertia about the bone cross section. Axial and bending stresses can then be used to estimate dorsal and plantar stresses:

$$\text{Dorsal stress: } \sigma_d = \sigma_{ax} + \sigma_{be}$$

$$\text{Plantar stress: } \sigma_p = \sigma_{ax} - \sigma_{be}$$

Ellison et al. described a number of model assumptions adopted from those made by Stokes et al. that were made to simplify the model. These include assuming that the plantar flexors share equal distribution of forces and act at a single point on the metatarsal bone, dorsal flexor contribution is negligible, kinetics and kinematics in the mediolateral direction are negligible, segment masses are negligible, the toe is a single segment, and the toe segment is perfectly parallel to the ground throughout contact.^{48,54} Model assumptions such as these are necessary when calculating bone loading parameters using a mathematical model based on beam theory. However, oversimplification of a model can cause inaccurate calculations.³⁵ Diminishing muscle contributions by simplifying the plantar flexors into one muscle and disregarding extensor muscles may provide inaccurate results because contractile muscle forces are often the largest force acting on bone.⁵⁶

Measuring Bone Stress in a Clinical Setting

In-clinic running gait analysis has been shown to be beneficial for minimizing injury risk and recovering from injury.⁵⁷ Availability of wearable sensors and applications to analyze kinematic and kinetic variables are increasingly affordable and available, making in-clinic gait analysis more accessible than ever.^{58,59} Quantifying metatarsal bone stress in a clinical setting may be beneficial in identifying a patient's risk for bone stress injury. However, while numerous

techniques for calculating metatarsal bone stress exist, none are practical for clinical use.^{54,60} The previously mentioned methods all require expensive equipment, time to analyze data, and expertise in various data collection and analysis techniques, none of which are typically available in a physical therapy or orthopedic clinic.^{61,62} Previous studies have suggested that a greater difference in pressure between the head and the base of the metatarsal is predictive of a greater metatarsal loading.⁶³ If true, this could provide a quick and inexpensive method of quantifying bone stress in a clinical setting while only requiring a pressure mat and software.

Metatarsal Stress during Running

Reported measures of bone stress during running vary greatly depending on methodology used. Although not representative of the average runner, many studies using indirect methods of measurement are performed barefoot in order to use marker sets appropriate for capturing accurate multi-segment foot kinematics.⁶⁴ Comparison between barefoot rearfoot and non-rearfoot strikers using a subject-specific beam theory model showed increased midshaft peak bending moments in the second metatarsal of the non-rearfoot group, but no differences in peak plantar or dorsal stresses.⁵⁴ However, peak stresses were reported to be higher than the point of failure for cortical bone. A study using a similar model without subject-specific geometry on shod runners reported far lower peak metatarsal stresses yet similar bending moments,⁵⁵ highlighting the differences that using subject specific models can make. Comparisons of all reported values of metatarsal loads estimated using indirect measurements were far greater than those reported by Milgrom et al. who utilized direct in vivo strain measurements during barefoot running.³⁹

Studies have also looked at the effect of footwear choice on metatarsal stress while running. When looking at metatarsal stress while running in different shoe types and at different stride lengths, FE models showed increased metatarsal strains and likelihood of failure in the second through fourth metatarsals when running in a minimalist shoe compared to a traditional shoe.⁶⁵ Additionally, decreasing stride length by 10% decreased fourth metatarsal strain. This suggests that switching to a minimalist shoe when used to a traditional shoe may be an injury risk.

Metatarsal Stress and Long-Distance Running

Long-distance runners are at a higher risk of bone stress injury; however, little is known regarding how metatarsal bone stress is affected by long-distance runs. Most current studies looking at kinetics during long run distances have focused on external loads. In general, studies looking at loading beneath the foot using plantar pressure measurements have seen increases in forefoot loading. Following a 20 km run at a self-selected pace, runners experienced increased peak and mean forces beneath the second, third, and fourth metatarsals, as well as a decrease in peak and mean force beneath the second through fourth toes.⁶⁶ Similarly, when looking at barefoot plantar pressure measurements before and after a marathon distance run, Nagel et al. saw a shift in peak pressure from beneath the toes to beneath the second through fourth metatarsals post run.⁶⁷ This pattern seems to stay consistent in even longer distance runs. After completion of a 246 km ultra-distance race, runners exhibited increased peak pressures beneath all five metatarsals and decreased peak pressures beneath all five toes.⁶⁸ The same shift in loading can also be seen during a shorter distance run at 80% of maximal effort,⁶⁹ although a distance run at near maximal effort is not common for most distance runners.⁷⁰ Decreases in

loading beneath the toe region are thought to be caused by fatigue in the toe flexor muscles. With less assistance from the toes,⁶⁷ the metatarsal region may need to apply more load to achieve the same push off result as when not fatigued. However, after completion of a 10km run, plantar pressure measurements showed no differences in pressure or force beneath the forefoot or toe region. Instead, the only change seen was a decrease in maximum force across the foot as a whole.⁷¹ This study involved a shorter, non-exhaustive run than the other studies and may not have been long enough to see the same effects of fatigue. Additionally, the participants ran at a slower pace than normal potentially making this a less difficult and fatiguing run. In the absence of metatarsal bone stress estimates during long runs, many of the above studies have suggested that external loads might be indicative of internal loading patterns. However, other studies have suggested that this may not be the case. Short distance running trials have suggested that ground reactions forces and loading metrics are not necessarily indicative of metatarsal or tibial loading patterns.^{54,72} Further research needs to be done to understand whether metatarsal bone stresses and bending moments increase a similar pattern as external loading parameters after a long-distance run.

Summary

Metatarsal stress fractures are common running-related overuse injuries. Stress fracture development is a result of repetitive, submaximal loading combined with an insufficient amount of recovery time for the bone remodeling cycle to take place. A large number of potential risk factors make the exact circumstances of stress fracture development difficult to determine. For runners, the high magnitude, high volume loading experienced during a run can be part of the cause and those who run farther distances experience even larger load volumes. While metatarsal

bone stress has been looked at during short distance, in different shoe types, and between different foot strike patterns, it is still unclear how metatarsal loads change after the completion of a long-distance run. Unfortunately, it can be quite difficult to determine the amount of metatarsal stress being experienced during a run. Methods for measuring bone stress include direct methods such as in vivo measurements on live participants using strain gauges and the use of similar instruments and dynamic movement simulators on cadaver specimens. Mathematical models can provide less invasive estimates of bone stress; however, they are still time and resource intensive. A quick, easy method for determining bone stress could be beneficial in determining injury risk in a clinical setting. The use of plantar pressure measurements as a surrogate measure of bone stress has potential of being a useful clinical tool. Therefore, the following thesis will attempt to characterize changes in metatarsal bone load after a long-distance run and investigate a potentially feasible method of estimating internal metatarsal bone loads using external measures.

References

1. Porter AK, Cuthbertson CC, Evenson KR. Participation in specific leisure-time activities and mortality risk among U.S. adults. *Ann Epidemiol.* 2020;50:27-34.e1. doi:10.1016/j.annepidem.2020.06.006
2. Dai S, Carroll DD, Watson KB, Paul P, Carlson SA, Fulton JE. Participation in Types of Physical Activities Among US Adults--National Health and Nutrition Examination Survey 1999-2006. *J Phys Act Health.* 2015;12:S128-S140. doi:10.1123/jpah.2015-0038
3. Hulteen RM, Smith JJ, Morgan PJ, et al. Global participation in sport and leisure-time physical activities: A systematic review and meta-analysis. *Prev Med (Baltim).* 2017;95:14-25. doi:10.1016/j.ypmed.2016.11.027
4. Pedisic Z, Shrestha N, Kovalchik S, et al. Is running associated with a lower risk of all-cause, cardiovascular and cancer mortality, and is the more the better? A systematic review and meta-analysis. *Br J Sports Med.* 2020;54(15):898-905.
5. Brené S, Bjørnebekk A, Åberg E, Mathé AA, Olson L, Werme M. Running is rewarding and antidepressive. *Physiol Behav.* 2007;92(1-2):136-140. doi:10.1016/j.physbeh.2007.05.015
6. Fields KB, Sykes JC, Walker KM, et al. Prevention of running injuries. *Curr Sports Med Rep.* 2010;9(3):176-182. www.acsm-csmr.org
7. van Poppel D, van der Worp M, Slabbekoorn A, et al. Risk factors for overuse injuries in short- and long-distance running: A systematic review. *J Sport Health Sci.* 2021;10(1):14-28. doi:10.1016/j.jshs.2020.06.006
8. Chen YT, Tenforde AS, Fredericson M. Update on stress fractures in female athletes: Epidemiology, treatment, and prevention. *Curr Rev Musculoskelet Med.* 2013;6(2):173-181. doi:10.1007/s12178-013-9167-x
9. Mayer SW, Joyner PW, Almekinders LC, Parekh SG. Stress Fractures of the Foot and Ankle in Athletes. *Sports Health.* 2014;6(6):481-491. doi:10.1177/1941738113486588
10. Chuckpaiwong B, Cook C, Pietrobon R, Nunley JA. Second metatarsal stress fracture in sport: Comparative risk factors between proximal and non-proximal locations. *Br J Sports Med.* 2007;41(8):510-514. doi:10.1136/bjsm.2006.033571
11. Saunier J, Chapurlat R. Stress fracture in athletes. *Joint Bone Spine.* 2018;85(3):307-310. doi:10.1016/j.jbspin.2017.04.013
12. Warden SJ, Davis IS, Fredericson M. Management and prevention of bone stress injuries in long-distance runners. *J Orthop Sports Phys Ther.* 2014;44(10):749-765. doi:10.2519/jospt.2014.5334

13. Bennell K, Matheson G, Meeuwisse W, Brukner P. Risk factors for stress fractures. *Sports Med.* 1999;28(2):91-122.
14. Chan C, Rudins A. Foot biomechanics during walking and running. *Mayo Clin Proc.* 1994;69(5):448-461. doi:10.1016/S0025-6196(12)61642-5
15. *Measurements Used to Characterize the Foot and the Medial Longitudinal Arch: Reliability and Validity.* <https://academic.oup.com/ptj/article/80/9/864/2842502>
16. Gwani AS, Asari MA, Ismail ZIM. How the three arches of the foot intercorrelate. *Folia Morphologica (Poland).* 2017;76(4):682-688. doi:10.5603/FM.a2017.0049
17. Hughes JM, Popp KL, Yanovich R, Bouxsein ML, Matheny RW. The role of adaptive bone formation in the etiology of stress fracture. *Exp Biol Med.* 2017;242(9):897-906. doi:10.1177/1535370216661646
18. Hadjidakis DJ, Androulakis II. Bone remodeling. In: *Annals of the New York Academy of Sciences.* Vol 1092. Blackwell Publishing Inc.; 2006:385-396. doi:10.1196/annals.1365.035
19. Hill PA. Bone Remodelling. *J Orthod.* 1998;25:101-107.
20. Matcuk GR, Mahanty SR, Skalski MR, Patel DB, White EA, Gottsegen CJ. Stress fractures: pathophysiology, clinical presentation, imaging features, and treatment options. *Emerg Radiol.* 2016;23(4):365-375. doi:10.1007/s10140-016-1390-5
21. Nalla RK, Kinney JH, Ritchie RO. Mechanistic fracture criteria for the failure of human cortical bone. *Nat Mater.* 2003;2(3):164-168. doi:10.1038/nmat832
22. Wolfram U, Schwiedrzik J. Post-yield and failure properties of cortical bone. *Bonekey Rep.* 2016;5. doi:10.1038/bonekey.2016.60
23. Fredericson M, Jennings F, Beaulieu C, Matheson GO. *Stress Fractures in Athletes.*; 1995. <http://journals.lww.com/topicsinmri>
24. Kaufman KR, Brodine SK, Shaffer RA, Johnson CW, Cullison TR. *The Effect of Foot Structure and Range of Motion on Musculoskeletal Overuse Injuries.* Vol 27.; 1993.
25. Rongstad KM, Tueting J, Rongstad M, Garrels K, Meis R. Fourth metatarsal base stress fractures in athletes: A case series. *Foot Ankle Int.* 2013;34(7):962-968. doi:10.1177/1071100713475613
26. Pegrum J, Dixit V, Padhiar N, Nugent I. The pathophysiology, diagnosis, and management of foot stress fractures. *Physician and Sportsmedicine.* 2014;42(4):87-99. doi:10.3810/psm.2014.11.2095
27. Nazem TG, Ackerman KE. The Female Athlete Triad. *Sports Health.* 2012;4(4):302-311. doi:10.1177/1941738112439685

28. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc.* 2006;38(2):323-328. doi:10.1249/01.mss.0000183477.75808.92
29. Tenforde AS, Sayres LC, McCurdy ML, Sainani KL, Fredericson M. Identifying sex-specific risk factors for stress fractures in adolescent runners. *Med Sci Sports Exerc.* 2013;45(10):1843-1851. doi:10.1249/MSS.0b013e3182963d75
30. Nunns M, Stiles V, Dixon S. The effects of standard issue Royal Marine recruit footwear on risk factors associated with third metatarsal stress fractures. *Footwear Sci.* 2012;4(1):59-70. doi:10.1080/19424280.2012.666388
31. Jandová S, Sparks M, Oleśniewicz P, Charousek J, Chrástková M, Markiewicz J. Changes in the foot strike pattern and pressure distribution when running in minimalist and traditional sport shoes. *Medicina dello Sport.* 2018;71(2):257-267. doi:10.23736/S0025-7826.18.03029-6
32. Hootman J, Macera C, Ainsworth B, Martin M, Addy C, Blair S. Predictors of lower extremity injury among recreationally active adults. *Clin J Sport Med.* . *Clin J Sport Med.* 2002;12(2):99-106.
33. Dixon S, Nunns M, House C, et al. Prospective study of biomechanical risk factors for second and third metatarsal stress fractures in military recruits. *J Sci Med Sport.* 2019;22(2):135-139. doi:10.1016/j.jsams.2018.06.015
34. Koh YG, Lee JA, Lee HY, Chun HJ, Kim HJ, Kang KT. Design optimization of high tibial osteotomy plates using finite element analysis for improved biomechanical effect. *J Orthop Surg Res.* 2019;14(1). doi:10.1186/s13018-019-1269-8
35. Al Nazer R, Lanovaz J, Kawalilak C, Johnston JD, Kontulainen S. Direct in vivo strain measurements in human bone-A systematic literature review. *J Biomech.* 2012;45(1):27-40. doi:10.1016/j.jbiomech.2011.08.004
36. Hoshaw SJ, Fyhrie DP, Takano Y, Burr1 \$ D B, Milgroms C. Technical note: A method suitable for in vivo measurement of bone strain in humans. *J Biomech.* 1997;30(5):521-524.
37. Arndt A, Ekenman I, Westblad P, Lundberg A. *Effects of Fatigue and Load Variation on Metatarsal Deformation Measured in Vivo during Barefoot Walking.* Vol 35.; 2002.
38. Arndt A, Westblad P, Ekenman I, Lundberg A. A comparison of external plantar loading and in vivo local metatarsal deformation wearing two different military boots. *Gait Posture.* 2003;18:20-26. www.elsevier.com/locate/gaitpost
39. Milgrom C, Finestone A, Sharkey N, et al. *Metatarsal Strains Are Sufficient to Cause Fatigue Fracture During Cyclic Overloading.*; 2002.

40. Yang PF, Bruggemann GP, Rittweger J. What do we currently know from in vivo bone strain measurements in humans? *Journal of Musculoskeletal and Neuronal Interaction*. 2011;11(1):8-20.
41. Selcuk İ, Tatar I, Huri E. Cadaveric anatomy and dissection in surgical training. *Turk J Obstet Gynecol*. 2019;16(1):72-75. doi:10.4274/tjod.galenos.2018.15931
42. Muehleman C, Lidtke R, Berzins A, et al. Contributions of bone density and geometry to the strength of the human second metatarsal. *Bone*. 2000;27(5):709-714.
43. Donahue SW, Sharkey NA, Modanlou KA, Sequeira LN, Martin RB. *Bone Strain and Microcracks at Stress Fracture Sites in Human Metatarsals*.; 2000.
44. Zysset PK, Dall'Ara E, Varga P, Pahr DH. Finite element analysis for prediction of bone strength. *Bonekey Rep*. 2013;2. doi:10.1038/bonekey.2013.120
45. Zhang Y, Awrejcewicz J, Szymanowska O, et al. Effects of severe hallux valgus on metatarsal stress and the metatarsophalangeal loading during balanced standing: A finite element analysis. *Comput Biol Med*. 2018;97:1-7. doi:10.1016/j.compbiomed.2018.04.010
46. Brilakis E, Kaselouris E, Xypnitos F, Provatidis CG, Efsthathopoulos N. Effects of Foot Posture on Fifth Metatarsal Fracture Healing: A Finite Element Study. *Journal of Foot and Ankle Surgery*. 2012;51(6):720-728. doi:10.1053/j.jfas.2012.08.006
47. Li Y, Leong KF, Gu Y. Construction and finite element analysis of a coupled finite element model of foot and barefoot running footwear. *Proc Inst Mech Eng P J Sport Eng Technol*. 2019;233(1):101-109. doi:10.1177/1754337118803540
48. Stokes IAF, Hutton WC, Stott JRR. Forces acting on the metatarsals during normal walking. *J Anat*. 1979;129(3):579-590.
49. Bauchau OA, Craig JI. Euler-Bernoulli beam theory. In: Bauchau OA, Craig JI, eds. *Structural Analysis*. Springer Netherlands; 2009:173-221. doi:10.1007/978-90-481-2516-6_5
50. Rybicki EF, Simonen FA, Weis EB. On the mathematical analysis of stress in the human femur. *J Biomech*. 1972;5:203-215.
51. Brassey CA, Margetts L, Kitchener AC, Withers PJ, Manning PL, Sellers WI. Finite element modelling versus classic beam theory: Comparing methods for stress estimation in a morphologically diverse sample of vertebrate long bones. *J R Soc Interface*. 2013;10(79). doi:10.1098/rsif.2012.0823
52. Arias-Moreno AJ, Ito K, van Rietbergen B. Accuracy of beam theory for estimating bone tissue modulus and yield stress from 3-point bending tests on rat femora. *J Biomech*. 2020;101. doi:10.1016/j.jbiomech.2020.109654

53. Nunns M, Stiles V, Fulford J, Dixon S. Estimated third metatarsal bending stresses are highly susceptible to variations in bone geometry. *Footwear Sci.* 2017;9(3):127-137. doi:10.1080/19424280.2017.1344326
54. Ellison MA, Kenny M, Fulford J, Javadi A, Rice HM. Incorporating subject-specific geometry to compare metatarsal stress during running with different foot strike patterns. *J Biomech.* 2020;105. doi:10.1016/j.jbiomech.2020.109792
55. Gross TS, Bunch RP. A mechanical model of metatarsal stress fracture during distance running*. *Am J Sports Med.* 1989;17(5):669-674.
56. Hart NH, Nimphius S, Rantalainen T, Ireland A, Siafarikas A, Newton RU. Mechanical basis of bone strength: influence of bone material, bone structure and muscle action. *J Musculoskelet Neuronal Interact.* 2017;17(3):114-139. <http://www.ismni.org>
57. Wren TAL, Gorton GE, Öunpuu S, Tucker CA. Efficacy of clinical gait analysis: A systematic review. *Gait Posture.* 2011;34(2):149-153. doi:10.1016/j.gaitpost.2011.03.027
58. Trinler U, Schwameder H, Baker R, Alexander N. Muscle force estimation in clinical gait analysis using AnyBody and OpenSim. *J Biomech.* 2019;86:55-63. doi:10.1016/j.jbiomech.2019.01.045
59. Higginson BK. *Methods of Running Gait Analysis.* Vol 8.; 2009. <http://journals.lww.com/acsm-csmr>
60. Gu YD, Ren XJ, Li JS, Lake MJ, Zhang QY, Zeng YJ. Computer simulation of stress distribution in the metatarsals at different inversion landing angles using the finite element method. *Int Orthop.* 2010;34(5):669-676. doi:10.1007/s00264-009-0856-4
61. Milgrom C, Finestone A, Hamel A, Mandes V, Burr D, Sharkey N. A comparison of bone strain measurements at anatomically relevant sites using surface gauges versus strain gauged bone staples. *J Biomech.* 2004;37(6):947-952. doi:10.1016/j.jbiomech.2003.10.008
62. Volf J, Novák V, Ryženko V, Bezouška V, Bláhová M. Transducer for in bone stress and remodelling measuring. In: *Measurement: Sensors.* Vol 18. Elsevier Ltd; 2021. doi:10.1016/j.measen.2021.100312
63. Orendurff MS, Rohr ES, Segal AD, Medley JW, Green JR, Kadel NJ. Biomechanical analysis of stresses to the fifth metatarsal bone during sports maneuvers: Implications for fifth metatarsal fractures. *Physician and Sportsmedicine.* 2009;37(2):87-92. doi:10.3810/psm.2009.06.1714
64. Leardini A, Benedetti MG, Berti L, Bettinelli D, Natio R, Giannini S. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait Posture.* 2007;25(3):453-462. doi:10.1016/j.gaitpost.2006.05.017

65. Firminger CR, Fung A, Loundagin LL, Edwards WB. Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics*. 2017;49:8-15. doi:10.1016/j.clinbiomech.2017.08.006
66. Willems TM, De Ridder R, Roosen P. The effect of a long-distance run on plantar pressure distribution during running. *Gait Posture*. 2012;35(3):405-409. doi:10.1016/j.gaitpost.2011.10.362
67. Nagel A, Fernholz F, Kibele C, Rosenbaum D. Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait Posture*. 2008;27(1):152-155. doi:10.1016/j.gaitpost.2006.12.012
68. Karagounis P, Prionas G, Armenis E, Tsiganos G, Baltopoulos P. The impact of the spartathlon ultramarathon race on athletes' plantar pressure patterns. *Foot Ankle Spec*. 2009;2(4):173-178. doi:10.1177/1938640009342894
69. Bisiaux M, Moretto P. The effects of fatigue on plantar pressure distribution in walking. *Gait Posture*. 2008;28(4):693-698. doi:10.1016/j.gaitpost.2008.05.009
70. Paquette MR, Melcher DA. Impact of a long run on injury-related biomechanics with relation to weekly mileage in trained male runners. *J Appl Biomech*. 2017;33(3):216-221. doi:10.1123/jab.2016-0170
71. Alfuth M, Rosenbaum D. Long distance running and acute effects on plantar foot sensitivity and plantar foot loading. *Neurosci Lett*. 2011;503(1):58-62. doi:10.1016/j.neulet.2011.08.010
72. Matijevich ES, Branscombe LM, Scott LR, Zelik KE. Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. *PLoS One*. 2019;14(1). doi:10.1371/journal.pone.0210000
73. Ferber R, Macdonald S. Running Mechanics and Gait Analysis. In: ; 2014.

CHAPTER THREE

ACUTE EFFECTS OF A NON-EXHAUSTIVE LONG RUN ON METATARSAL
BONE LOADS

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

Author: Kaitlyn McKibben

Contributions: Development of research question, data collection, analysis and processing,
writing, revision and editing of manuscript

Co-Author: Scott Monfort

Contributions: Revision and editing of manuscript

Co-Author: John Seifert

Contributions: Revision and editing of manuscript

Co-Author: James Becker

Contributions: Development of research question, study design, performing data
collection, data processing and analysis, revisions and editing of manuscript

Manuscript Information

Kaitlyn McKibben, Scott Monfort, John Seifert, and James Becker

Status of Manuscript:

☒ Prepared for submission to a peer-reviewed journal

☐ Officially submitted to a peer-reviewed journal

☐ Accepted by a peer-reviewed journal

☐ Published in a peer-reviewed journal

Acute Effects of a Non-Exhaustive Long Run on Metatarsal Bone Loads

Kaitlyn McKibben and James Becker

Department of Health and Human Development, Montana State University, Bozeman, MT USA

Corresponding Author:

Dr. James Becker

219 Herrick Hall

Department of Health & Human Development

Montana State University

Bozeman, MT 59717 USA

Email: james.becker4@montana.edu

Word Count: 5921

Abstract

Metatarsal stress fractures make up almost 9% of all running injuries and long-distance runners who experience greater volumes of bone loading may be at a higher risk for developing stress fracture injuries. While the influence of footwear and footstrike pattern on metatarsal loading have been previously reported, it remains unclear how run duration influences metatarsal loads. PURPOSE: To compare changes in metatarsal bone loading parameters at the beginning and end of a long-distance run. METHODS: Nineteen long-distance runners (12 female; 21.57 ± 3.53 years; 70.01 ± 10.79 kg) ran a distance equivalent to 25% of their weekly mileage on an instrumented treadmill at a self-selected pace. Whole body kinematics, ground reaction forces, and in-shoe plantar pressures were recorded pre and post long run. Plantar and dorsal stresses, and midshaft bending moments were calculated using a musculoskeletal model of the metatarsals. Paired t-tests were used to compare mean peak loads between pre and post long run. RESULTS: Post run, peak plantar stresses increased 8% in the second ($p < 0.001$, $d = 0.25$) and third ($p < 0.001$, $d = 0.18$) metatarsals. Peak dorsal stresses increased 5% in the second ($p = 0.040$, $d = 0.16$) and 6% in the third ($p = 0.017$, $d = 0.13$) metatarsals. Peak midshaft bending moments increased 8% in the second ($p < 0.001$, $d = 0.25$) and 7% in the third ($p < 0.001$, $d = 0.18$) metatarsals. CONCLUSION: A non-exhaustive long run can increase metatarsal bone loading parameters in the second and third metatarsals, potentially increasing injury risk.

Introduction

Running is a popular activity with around 50 million participants in the United States.¹⁶ Although running is associated with numerous health benefits, overuse injuries are common and nearly half of all runners will experience a running related injury in a given year.^{16,35} Stress fracture injuries are particularly common and make up nearly 16% of all running injuries, with 9% of these affecting the metatarsals.^{9,33} While stress fracture etiology is multifactorial and can be influenced by anatomical and physiological factors, mechanical factors such as increased bone loading without proper recovery time are a large contributor to injury risk.³⁶

Running is a high load, high volume activity making it an ideal activity for stress fracture development. Runners experience repetitive gait cycles with forces up to three times greater than their body weight at each foot contact.⁷ This magnitude and volume of loading, combined with a lack of recovery time, can lead to a disruption of the bone remodeling cycle and push a bone past its injury threshold, contributing to stress fracture risk.⁴⁶ This can be especially concerning for long-distance runners who experience far greater load volumes during a standard run than those who run shorter distances. Long-distance runners are particularly prone to injury with up to 79% of distance runners experiencing a running related injury each year,¹⁹ and those who run more than 20 miles per week are considered at a greater risk of lower extremity injury.²⁶ While incidence of metatarsal stress fractures remains around 8-9% regardless of run duration,³ the amount of total stress fractures in distance runners increases to 31% all of running-related injuries,²⁸ suggesting a relatively larger number of metatarsal stress fractures compared to those who run shorter distances.

The increased injury incidence in long distance runners may be due to the altered loading patterns occurring following long-distance runs.^{34,51} Following a 20 km run there are increases in peak force beneath the second, third, and fourth metatarsals and decreases in peak forces under the rearfoot and toe.⁴⁹ Plantar pressure measurements taken post marathon also show a transfer of loading from beneath the toes to beneath the metatarsal heads with no differences in rearfoot loading compared to the beginning of the run.³⁷ Following an exhaustive run above anaerobic threshold, forces and peak plantar pressure increase beneath the metatarsal and toe regions.⁴⁸ Lastly, increases in peak pressure beneath the second and third metatarsal and first toe, and decreases in rearfoot pressure have also been seen following a 30 minute run at 80% of maximal aerobic speed.⁵

Despite consistently reporting an increase in overall forefoot loading after a long run, studies disagree on which specific regions are affected, the magnitude of the changes, and the implications of the increases. One potential explanation for this disagreement is the wide variation in distances and intensities used for a “long run”, with some studies using runs as short as 3 km and others using runs greater than 200 km.^{27,48} Within this range, some studies include maximal effort runs or strenuous but submaximal runs to induce fatigue-related changes to gait. In contrast, protocols which evaluate changes in load following an easy run equivalent to 25% of weekly training volume may be more representative, as such easy paced long runs are a staple part of many runners training programs.⁴⁰

Furthermore, while several studies have suggested that increased forefoot loading after a long run may be indicative of greater bone stress and increased injury risk,^{39,45,52} it is unclear whether actual stresses experienced by the metatarsals follow the same pattern. Some authors

have suggested that ground reaction forces and plantar pressures measured during running may not be representative of internal loading in the bones.^{15,32} Thus, whether changes in external loading following a long run results in increased metatarsal bone stress remains an unanswered question. Given this gap in knowledge, the purpose of this study was to characterize changes in metatarsal bone stress before and after a non-exhaustive long-distance run using a mathematical model of the metatarsals. We hypothesized that peak plantar stress, dorsal stress, and midshaft bending moments would be greater at the completion of the run and that increases in bone loading post run would be greatest in the second and third metatarsals.

Methods

Participants

Twenty-one long-distance runners participated in this study (sex: 14F, 7M; age: 22.76 ± 2.14 years; height: 1.74 ± 0.71 m; mass: 69.21 ± 10.55 kg; average mileage: 29.81 ± 8.96 miles per week). Participants were recruited from local running clubs and the college community. Inclusion criteria included running at least 25 miles per week for the past three months while completing one long run per week consisting of at least 25% of the weekly mileage, being injury free at the time of testing with no injury in the previous six months, and no history of metatarsal stress fracture. Prior to participation, all participants provided written informed consent. All protocols in this study were approved by the University's Institutional Review Board.

Protocol

Following a five-minute warmup on an instrumented treadmill (Treadmetrix, Park City, UT) at a self-selected pace, participants ran at an easy training pace (2.83 ± 0.31 m/s) for a

distance equivalent to 25% of their average weekly mileage (7.10 ± 0.93 miles). Rather than completing an exhaustive run, this distance was chosen to better imitate the prolonged, submaximal effort runs that are commonly completed by long-distance runners.⁴⁰ For the first five minutes of the run, participants ran in a neutral laboratory provided shoe (New Balance Fresh Foam 1080) equipped with plantar pressure insoles (Tekscan, Boston, MA). Due to the potential for pressure insoles to alter running mechanics over time,³⁰ the majority of the run was completed in each participant's own regular training shoes. For the final five minutes, participants switched back into laboratory provided shoes. Switching between shoes and equipment was done as quickly as possible to avoid any attenuation of fatigue-related changes to running gait (187.72 ± 37.69 seconds).²¹

Whole body kinematics were recorded during the final 30 seconds of the first and last five minutes of the run using a 6-camera motion capture system (Motion Analysis Corp., Santa Rosa, CA) sampling at 250 Hz. Ground reaction forces and plantar pressure measurements were recorded at 1000 Hz and 250 Hz, respectively. Plantar pressure insoles were trimmed to fit each participant's provided shoe and adhered to the shoe insole. Insoles were made up of up to 960 pressure sensels (depending on the trimmed size) with 3.9 sensels/cm². Foot kinematics were quantified using a multi-segment foot model with reflective markers placed on the shoe on the head and base of the first and fifth metatarsals, head of the second metatarsal, and navicular tuberosity.⁴ Two markers were aligned vertically on the posterior heel with the top marker aligned horizontally with the second metatarsal marker, and a third marker was placed on the lateral aspect of the heel. Additional markers were placed on the anterior superior iliac spines, iliac crests, posterior superior iliac spines, medial and lateral femoral epicondyles, tibial

tuberosities and the medial and lateral malleoli. Clusters of four markers were placed on the lateral thigh and shank.

Data Analysis

Marker trajectories were tracked in Cortex software (Motion Analysis Corp, Rohnert Park, CA) where they were filtered with a zero-lag, lowpass Butterworth filter with a cutoff frequency of 8 Hz. Masks were applied to peak pressure footprints in the F-Scan Research software (Tekscan Inc., Boston MA) to determine peak pressure and normal force values under the metatarsal heads, as well as toe lengths. To measure metatarsal lengths, the distance between the fifth metatarsal head and base markers was calculated. This metatarsal length was measured because the head and the base of the fifth metatarsal are the easiest metatarsal landmarks to accurately locate through a shoe. This value was then scaled based on anthropometric measurements to estimate the length of the first, second, third, and fourth metatarsals.¹⁴ The orientation of the metatarsals relative to the floor was calculated using a YZX Cardan rotation sequence with the Y rotation corresponding to flexion/extension at the metatarsophalangeal joint.

Plantar stresses, dorsal stresses and midshaft bending moments acting on the shaft of the metatarsals were calculated using a musculoskeletal model, described in detail elsewhere^{15,20}, and custom Matlab code (MathWorks, Natick, MA). In brief, the model uses beam theory to estimate metatarsal loads. Motion capture data was used to determine the angle of the metatarsals relative to their position during normal standing. Ground reaction forces beneath the toes and metatarsal heads were estimated using mask placements in F-Scan Research software and used to calculate joint reaction forces at the metatarsophalangeal joint. Along with previously reported estimates of metatarsal radii^{20,44}, metatarsophalangeal joint reaction forces and metatarsal length

are then used to calculate axial forces, shear forces, and midshaft bending moments acting on the shaft of the metatarsal. Finally, forces, bending moments, and previously reported estimates of metatarsal cross-sectional area^{20,44} are used to estimate the tensile and compressive stresses acting at the midpoint of the metatarsal shaft. Model assumptions include assuming the toe is one segment, that flexor muscles act a single point on the metatarsal, and kinetics and kinematics in the mediolateral direction and segment masses are negligible.^{15,20} Plantar stresses, dorsal stresses, and midshaft bending moments were normalized to 100% of stance phase of the gait cycle.

Statistical Analysis

Five gait cycles per participant were analyzed in both the pre and post run conditions. All variables were assessed for normality using Shapiro-Wilk tests. Paired t-tests were used to compare mean peak plantar stress, dorsal stress, and midshaft bending moment values between the beginning and end of the run for each metatarsal on the right foot while statistical parametric mapping was used to compare mean curves across stance phase.⁴² Cohen's *d* effect sizes were reported to aid in interpretation of results. All statistical tests were performed using Statistical Package for the Social Sciences (SPSS, Version 25; IBM Corp., Armonk, NY) with significance levels set to $p \leq 0.05$.

Results

Inspection of center of pressure trajectories revealed that eighteen of the original twenty-one participants maintained their foot strike pattern throughout the duration of the run. Metatarsal loading may change with foot strike pattern,^{15,47} thus the final analysis was only performed using the 18 participants. Tests for normality indicated that all variables were

normally distributed ($p > 0.05$). Post run, peak plantar stresses increased 8% in the second ($p < 0.001$, $d = 0.25$) and third ($p < 0.001$, $d = 0.18$) metatarsals. Peak dorsal stresses also increased 5% in the second ($p = 0.040$, $d = 0.16$) and 6% in the third ($p = 0.017$, $d = 0.13$) metatarsals. Peak midshaft bending moments also increased 8% in the second ($p < 0.001$, $d = 0.25$) and 7% in the third ($p < 0.001$, $d = 0.18$) metatarsals after the run. There were no differences in any mean peak stresses or bending moments in the first, fourth, or fifth metatarsals (Figure 1). Vertical ground reaction forces (vGRF) beneath the second third, and fourth metatarsal heads, as well as total vGRF across all five metatarsals all increased from pre run to post run (Table 1).

	vGRF beneath the Met Heads (N)			
	Pre	Post	p	d
1 st met	207.22 ($\pm$ 67.34)	208.76 ($\pm$ 61.58)	0.742	0.02
2 nd met	142.48 ($\pm$ 50.45)	158.51 ($\pm$ 51.40)	< 0.001*	0.31
3 rd met	154.16 ($\pm$ 60.78)	169.38 ($\pm$ 63.85)	<0.001*	0.24
4 th met	101.13 ($\pm$ 34.84)	109.31 ($\pm$ 35.70)	0.049*	0.23
5 th met	81.10 ($\pm$ 23.38)	80.83 ($\pm$ 24.03)	0.925	0.01
Total	686.09 ($\pm$ 183.29)	736.79 ($\pm$ 174.57)	<0.001*	0.23

Table 1. Mean ($\pm$ standard deviation) of vertical ground reaction forces (vGRF) beneath each metatarsal head pre and post run. *denotes statistical significance

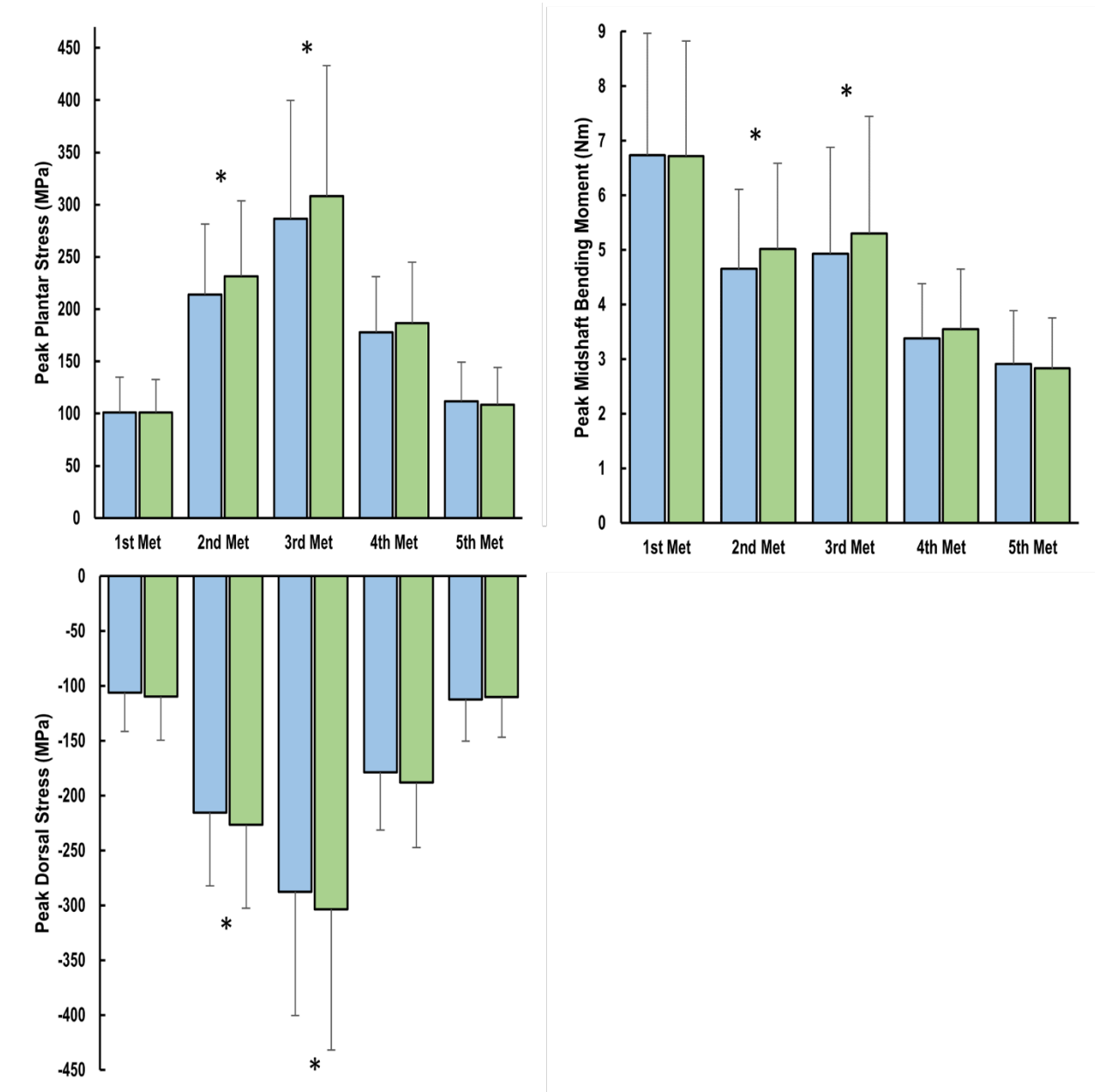


Figure 1. Mean peak plantar stress, dorsal stress, and midshaft bending moment values for each of the five metatarsals. Blue represents pre long-distance run. Green represents post long-distance run. Positive stress values indicate tension. Negative stress values indicate compressive stress.

Statistical parametric mapping revealed that post run, second metatarsal plantar stresses were greater during 42-82% ($p < 0.001$), dorsal stresses greater between 33-81% ($p < 0.001$), and midshaft bending moments greater between 36-41% ($p < 0.001$) and 46-81% ($p < 0.001$) of stance phase (Figure 2). In the third metatarsal, plantar stress, dorsal stress, and midshaft bending moments were all greater post run between 66-69% ($p = 0.001$) of stance phase. Third metatarsal plantar stresses were also greater post run between 54-58% ($p < 0.001$), dorsal stresses greater between 55-57% ($p < 0.001$), and midshaft bending moments greater between 55-58% ($p < 0.001$) of stance phase. There were no differences in mean stresses or bending moments across time between pre and post run in any of the other metatarsals. Time of peak dorsal stress in the first metatarsal was greater post run ($p = 0.042$, $d = 0.23$). There were no other differences in time of peak plantar stress, dorsal stress, or midshaft bending moment during the stance phase of gait between pre and post run (Table 2).

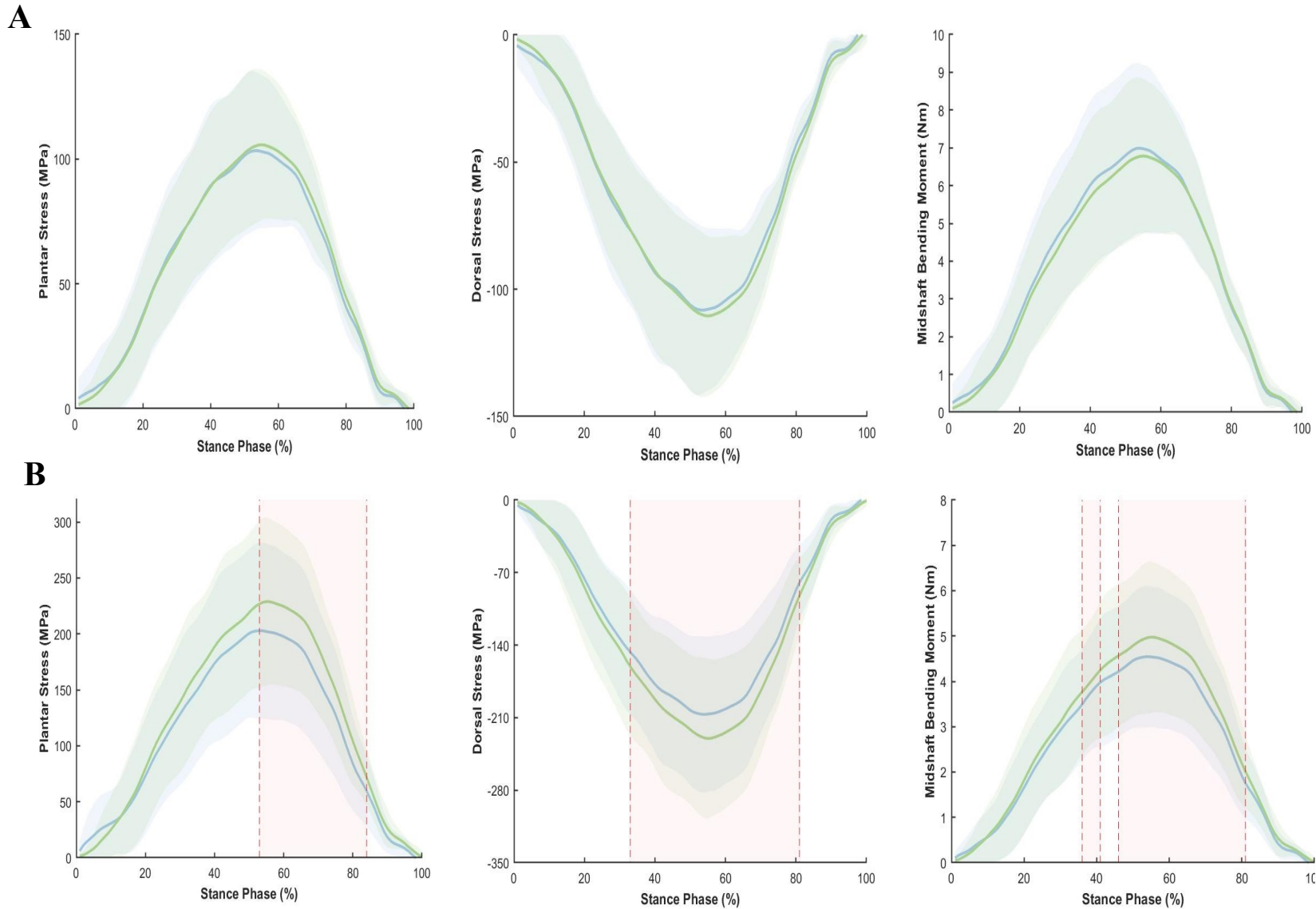
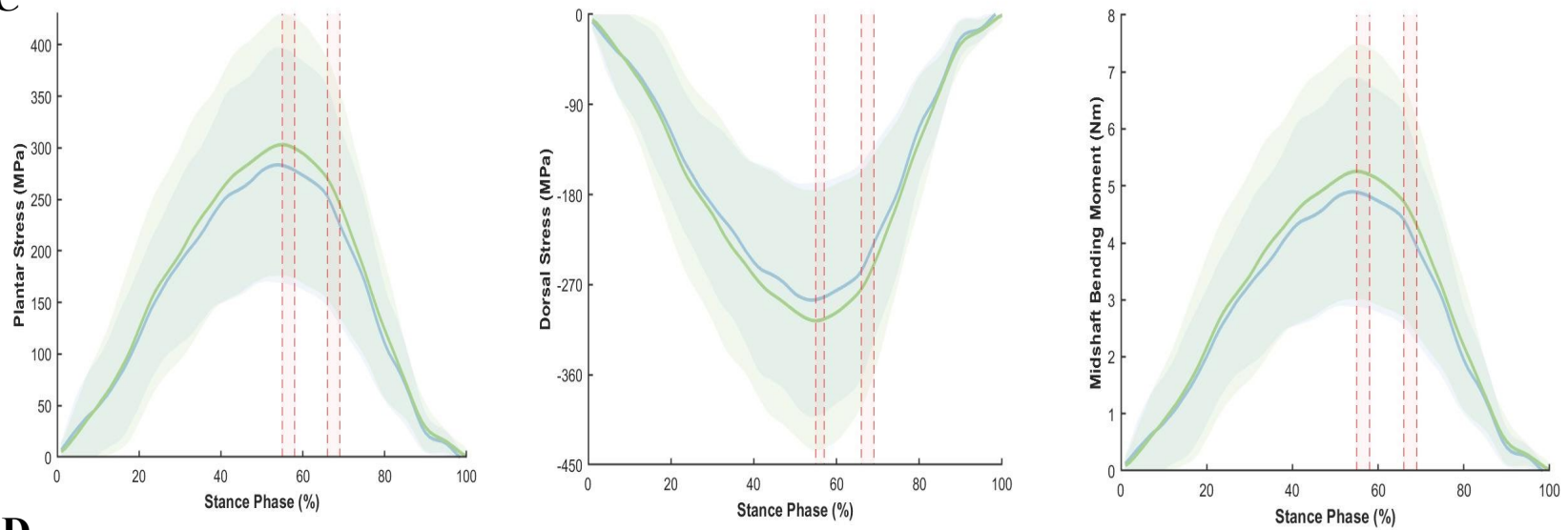


Figure 2. Differences between plantar stress, dorsal stress, and midshaft bending moments pre (blue) and post (green) run for the 1st (A), 2nd (B), 3rd (C), 4th (D), and 5th (E) metatarsals. Red indicates areas of statistical difference between pre and post run ($p < 0.05$). Positive stress values indicate tension. Negative stress values indicate compression.

C



D

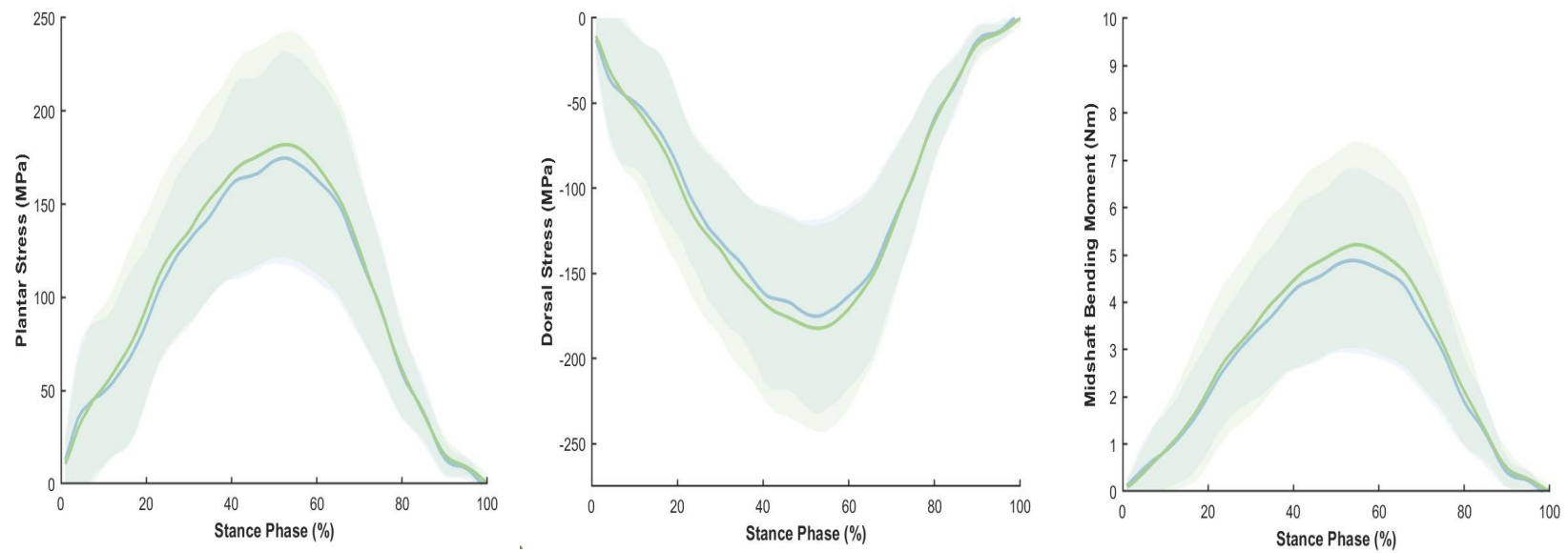


Figure 2 continued.

E

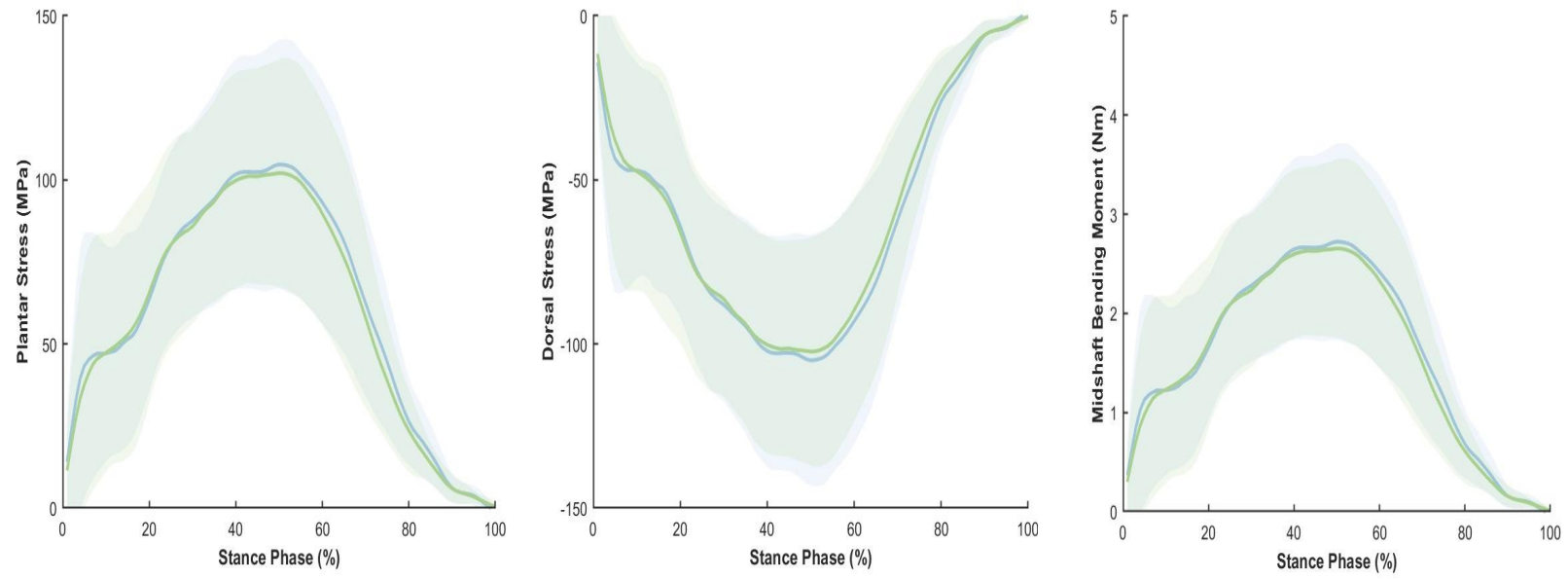


Figure 2 continued.

	Time of Peak Plantar Stress (% Stance)		Time of Peak Dorsal Stress (% Stance)		Time of Peak Midshaft Bending Moment (% Stance)	
	Pre	Post	Pre	Post	Pre	Post
1 st met	56.06 ($\pm$ 5.44)	56.00 ($\pm$ 5.67)	55.94 ($\pm$ 5.50)	57.22 ($\pm$ 6.19)*	56.33 ($\pm$ 5.29)	56.67 ($\pm$ 5.99)
2 nd met	57.17 ($\pm$ 6.61)	57.56 ($\pm$ 6.18)	57.11 ($\pm$ 6.50)	57.11 ($\pm$ 6.54)	57.17 ($\pm$ 6.51)	57.11 ($\pm$ 6.54)
3 rd met	55.56 ($\pm$ 6.52)	56.94 ($\pm$ 6.58)	55.56 ($\pm$ 6.57)	56.89 ($\pm$ 6.61)	55.61 ($\pm$ 6.59)	56.94 ($\pm$ 6.56)
4 th met	53.17 ($\pm$ 6.93)	51.39 ($\pm$ 9.91)	53.01 ($\pm$ 6.92)	51.33 ($\pm$ 9.91)	53.06 ($\pm$ 6.92)	51.39 ($\pm$ 9.91)
5 th met	43.56 ($\pm$ 15.77)	45.17 ($\pm$ 11.40)	43.56 ($\pm$ 15.77)	44.50 ($\pm$ 11.11)	43.56 ($\pm$ 15.77)	45.17 ($\pm$ 11.40)

Table 2. Time of peak plantar stress, dorsal stress, and midshaft bending moments across stance phase (Mean $\pm$ standard deviation). * indicates statistical significance

Discussion

The purpose of this study was to compare changes in metatarsal bone loading parameters before and after completion of a non-exhaustive, long-distance run using a mathematical model of the metatarsals. The main findings, in partial support of our hypothesis, were that peak plantar stress, dorsal stress, and midshaft bending moments increased following the long run. However, this was only true for the second and third metatarsals and there were no differences in peak plantar stress, dorsal stress, or midshaft bending moments in the first, fourth, or fifth metatarsals post run.

Pre run peak plantar stress, dorsal stress, and midshaft bending moment values are comparable with previously reported values, although direct comparisons between studies is difficult given methodological differences. While the pre-run values for peak plantar stress and dorsal stress in the second metatarsal from the current study are within one standard deviation of those reported by Ellison et al.,¹⁵ the peak midshaft bending moment values were substantially lower. Gross & Bunch²⁰ reported larger peak stress values for all five meta

tarsals and differences in midshaft bending moments compared to our results, including a negative first metatarsal midshaft bending moment and larger second and fifth metatarsal midshaft bending moments. Finally, Stokes et al.⁴⁴ reported similar peak midshaft bending moment values for the second, fourth, and fifth metatarsals, but larger first metatarsal and smaller third metatarsal peak midshaft bending moment values than this study. Discrepancies in results are most likely due to differing methodologies. While the mathematical model of the metatarsals and calculations to solve for stresses and bending moments were similar across studies, the exact implementation and input parameters varied. Stokes et al.⁴⁴ examined metatarsal loading during walking, which typically creates smaller loads, while the current study did so during running. Differences in gait mechanics between walking and running could explain differences in reported midshaft bending moment values. To calculate stress values, Ellison et al.¹⁵ incorporated subject-specific geometry into their model while our study used previously reported measurements of metatarsal length, radii, and cross-sectional area scaled by participant anthropometrics.^{14,20,44} This could account for the differences in second metatarsal midshaft bending moments as the equation is sensitive to the length and radius of the metatarsal head. Further, Ellison et al. analyzed barefoot running while the current study looked at shod running.

Further discrepancies in the model outputs could be due to the vGRF values used as inputs to the model. Ellison et al.¹⁵ and Stokes & Bunch⁴⁴ both reported much larger forces beneath the second metatarsal head than those found in the current study. This may be because vGRF values reported by Ellison et al. were measured using a larger anatomical region beneath the second metatarsal,⁴³ while this study used smaller anatomical regions that were similar in size to those described by Gross & Bunch.²⁰ However, despite using similar sized anatomical

regions, Gross & Bunch reported higher force values beneath the metatarsals.²⁰ This may be explained by their use of transducers beneath each region to measure force and reporting total ground reaction force while the current study used plantar pressure insoles to section out areas of force measured from a force plate and only reported the vertical component of the GRF. Further, even slight differences in boundary definitions of anatomical regions have been shown to affect pressure and force readings,⁴¹ suggesting that differing methodologies used to partition ground reaction forces from pressure footprints can yield different results. Combined, these discrepancies in results between studies that use the same overall model but with differing executions of inputs support the recommendation by Ellison et al. that this method of calculating metatarsal bone loads may best be interpreted when comparing relative values within studies rather than absolutes,¹⁵ especially in the absence of subject-specific metatarsal geometry.

Several studies have described increases in plantar loading beneath the forefoot after the completion of long runs at various distances.^{1,29,37,49} The results of the current study support these findings, showing increases in vGRF beneath the second, third, and fourth metatarsals after a non-exhaustive long run. Many of these same studies have subsequently inferred that an increase in external load could translate to an increase in internal metatarsal bone loads, however this assumption may not apply to the first, fourth, or fifth metatarsals. Our results show that plantar stress, dorsal stress, and midshaft bending moments were only greater in the second and third metatarsals following a long-distance run that is equivalent to many runners' weekly long run. Increases in bone load could signal a potential increase in injury risk, especially in the second and third metatarsals where 80-90% of all metatarsal stress fractures in runners occur.¹⁰ Greater susceptibility to stress fracture is due in part to smaller cross-sectional areas and larger

magnitudes of external load experienced during running gait in comparison to other metatarsals.²⁰ During typical running gait, the middle forefoot beneath the second and third metatarsal heads experiences the highest loads compared to the medial and lateral forefoot.¹¹ Additionally, the largest increases in stress observed post run were in plantar values. During the stance phase of running gait, the plantar side of the bone is in tension and the dorsal side is in compression. Because cortical bone is weaker in tension than compression,²⁴ a greater increase in plantar stress may be a further indicator of increased bone stress injury risk.

Statistical parametric analysis showed that in addition to peak values being different, bone loading measures in the second and third metatarsals were also different across certain time points during stance phase. In the second metatarsal plantar stress, dorsal stress, and midshaft bending moments were all greater post run during ~40-80% of stance phase. This time corresponds with much of the propulsive phase of running gait. The second metatarsal experiences the highest external loads and impulses in the forefoot during the propulsive phase potentially due to longer contact times compared to the other metatarsals.¹² Contact times and forefoot loading are both known to increase with fatigue which could help explain the significant differences in second metatarsal loads pre and post run during this period. The second metatarsal also acts as a rigid lever during the propulsive portion of stance phase, whereas the other four metatarsals have more motion.⁸ While this does allow for more load to be transferred through the second metatarsal, the lack of flexibility compared to the other less rigid metatarsals may be a concern for injury risk. Additionally, plantar stress, dorsal stress, and midshaft bending moments in the third metatarsal were all greater post run between ~54-58% and 66-69% of stance phase. In both the second metatarsal and the third metatarsal, mean peak plantar stress, dorsal stress,

and midshaft bending moments occurred at time points where there were significant differences in loading pre and post run. Additionally, delayed medial forefoot loading has been suggested as an indicator of third metatarsal stress fracture risk most likely due to increased loading of the region beneath that metatarsal.¹³ The only significant change in time for mean peak loading parameters was seen in a later first metatarsal dorsal stress at post run, suggesting more time spent loading the lateral side of the foot, potentially as a result of fatigue.

Footstrike pattern was not explicitly controlled for in this study and participants used a mix of rearfoot strike (RFS) and non-rearfoot strike (NRFS) patterns, as determined by center of pressure trajectories from plantar pressure measurements. Eighteen of the twenty-one original participants maintained their chosen footstrike pattern throughout the duration of the run while the remaining three modified their footstrike from beginning to end and were therefore not included in the final data set. Evidence of changes to footstrike can be seen in total vGRF values beneath the metatarsal heads (Figure 3). While those who maintained their footstrike pattern saw increased forefoot loading at the completion of the run, those who changed footstrike pattern experienced decreases in vGRF as they migrated further back on their foot. Modifications in loading patterns at the onset of fatigue are not uncommon. Increases in forefoot loading due to shifts in load from beneath the toes to the forefoot region, especially in the second and third metatarsals,⁴⁹ and decreases in rearfoot loading are often seen at the end of non-exhaustive long runs in runners who do not switch their foot strike pattern.¹ However, studies reporting gait modifications in distance running indicate that changes in actual foot strike pattern are a less common phenomenon. Only 11% of runners modify their foot strike pattern, and most often change from NRFS to RFS as distance increases and fatigue sets in.^{6,22,23} Uniquely, the three

participants who displayed changing foot strike patterns were the only women in the study who consistently ran more than 30 miles per week at the time of data collection and had all participated in multiple ultra-distance races. It is possible that changing foot strike pattern in response to fatigue during an exhaustive race is a behavior that also translates to less exhaustive distance runs. Even then, the individualized responses were different across participants. While having a natural RFS, Subject 01 reported changing to a NRFS in recent years but tends to revert to a RFS when fatigued. Compared to the other two participants who changed foot strikes, Subject 01 did not have a large decrease in overall total vGRF. Instead, there was a shift in loading post run from beneath the first metatarsal to beneath the fifth metatarsal while the other three metatarsals remained similar between conditions. Subject 12 began the run with a NRFS and ended with a RFS. This could be a result of overstriding as the runner becomes more fatigued as increased step lengths have been seen at the end of long runs.^{18,50} Finally, subject 21 began the run with a RFS but by the end of the run adopted a more pronounced RFS pattern, evidenced by a larger impact peak and lessened loading beneath the forefoot and toe region. Like Subject 12, overstriding due to fatigue may have impacted foot strike. While previous studies have compared between consistent footstrike patterns, these individualized responses suggest that further evaluation of changes in metatarsal bone loading in runners who switch between foot strike patterns over the course of a run is needed.

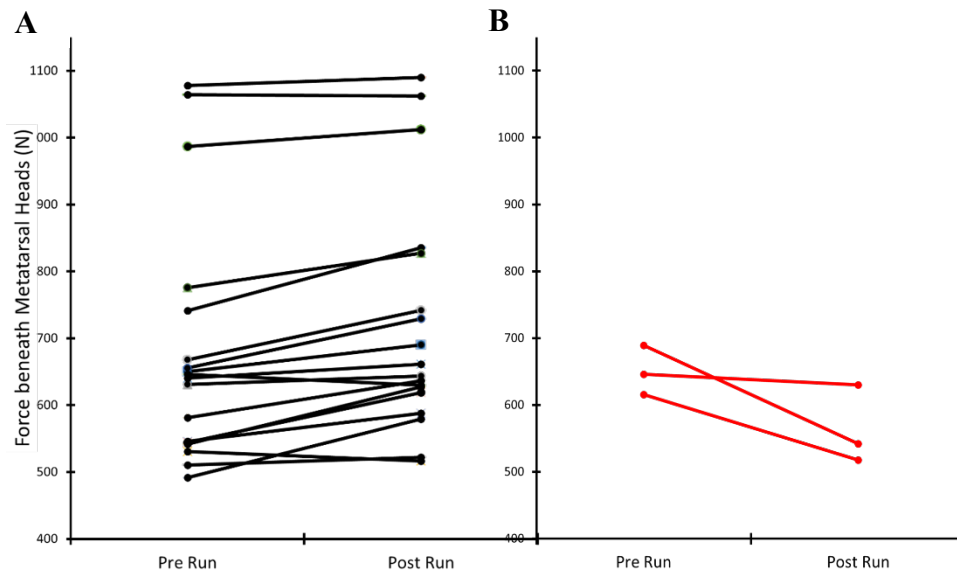


Figure 3. Total vertical ground reaction forces beneath all five metatarsal heads pre and post run for the participants who maintained footstrike pattern throughout the run (A) and the participants who modified their footstrike pattern (B).

There were several limitations should be considered when evaluating the results of this study. First, while the mathematical model of the metatarsals provides a noninvasive method to estimate metatarsal stresses, it does have limitations including a lack of subject-specific modelling. Structure of the metatarsal bones varies between individuals and using beam theory to model the bones is an oversimplification as metatarsal stresses and bending moments are highly susceptible to changes in geometry.³⁸ The model also simplifies the musculature of the foot into one plantar flexor muscle and no extensors muscles, does not consider bone deformations, and does not consider the influence of shoe padding. Several studies have found that shoe type can affect distribution of ground reaction forces.^{2,31} While shoe type was controlled for in the current study, the results do not necessarily extend to footwear with different construction or amounts of cushioning. As discussed above, results of this study are best evaluated as relative changes pre and post long-distance run instead of as absolutes. Secondly, before collecting the post run data,

participants were required to stop running to switch into laboratory provided shoes and plantar pressure insoles before finishing the run. This process may have attenuated some of the fatigue-related changes to running gait, however, participants resumed running well before the four minutes in which gait alterations are thought to dissipate.²¹ Finally, almost all participants were exclusively road and trail runners, and a long-distance treadmill run may not be indicative of stresses experienced during a long-distance road or trail run.^{17,25}

Conclusion

A long-distance run equivalent to many runners weekly long run increases plantar stress, dorsal stress, and midshaft bending moments in the second and third metatarsals. vGRF are also increased post run in the second, third, and fourth metatarsals. This may be detrimental as the second and third metatarsals are more susceptible to stress fracture in comparison to other metatarsals due to their slim shape and the amount of load experienced during a run.

References

1. Alfuth M, Rosenbaum D. Long distance running and acute effects on plantar foot sensitivity and plantar foot loading. *Neurosci Lett*. 2011;503(1):58-62.
2. Bates BT, Osternig LR, Sawhill JA, James SL. An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data. *J Biomech*. 1983;16(3):181-191.
3. Bennell KL, Malcolm SA, Thomas SA, Wark JD, Brukner PD. The incidence and distribution of stress fractures in competitive track and field athletes a twelve-month prospective study. *Am J Sports Med*. 1996;24(2):211-217.
4. Bishop C, Paul G, Thewlis D. The reliability, accuracy and minimal detectable difference of a multi-segment kinematic model of the foot-shoe complex. *Gait Posture*. 2013;37(4):552-557.
5. Bisiaux M, Moretto P. The effects of fatigue on plantar pressure distribution in walking. *Gait Posture*. 2008;28(4):693-698.
6. Bovalino SP, Kingsley MIC. Foot strike patterns during overground distance running: A systematic review and meta-analysis. *Sports Med Open*. 2021;7(1).
7. Cavanagh PR, LaFortune MA. Ground reaction forces in distance running*. *J Biomech*. 1980;13:397-406.
8. Chan C, Rudins A. Foot biomechanics during walking and running. *Mayo Clin Proc*. 1994;69(5):448-461.
9. Chen YT, Tenforde AS, Fredericson M. Update on stress fractures in female athletes: Epidemiology, treatment, and prevention. *Curr Rev Musculoskelet Med*. 2013;6(2):173-181.
10. Chuckpaiwong B, Cook C, Pietrobon R, Nunley JA. Second metatarsal stress fracture in sport: Comparative risk factors between proximal and non-proximal locations. *Br J Sports Med*. 2007;41(8):510-514.
11. Chuckpaiwong B, Nunley JA, Mall NA, Queen RM. The effect of foot type on in-shoe plantar pressure during walking and running. *Gait Posture*. 2008;28(3):405-411.
12. De Cock A, Willems T, Witvrouw E, Vanrenterghem J, De Clercq D. A functional foot type classification with cluster analysis based on plantar pressure distribution during jogging. *Gait Posture*. 2006;23(3):339-347.

13. Dixon S, Nunns M, House C, et al. Prospective study of biomechanical risk factors for second and third metatarsal stress fractures in military recruits. *J Sci Med Sport*. 2019;22(2):135-139.
14. Dogan A, Uslu M, Aydinlioglu A, Harman M, Akpinar F. Morphometric study of the human metatarsals and phalanges. *Clinical Anatomy*. 2007;20(2):209-214.
15. Ellison MA, Kenny M, Fulford J, Javadi A, Rice HM. Incorporating subject-specific geometry to compare metatarsal stress during running with different foot strike patterns. *J Biomech*. 2020;105.
16. Fields KB, Sykes JC, Walker KM, et al. Prevention of running injuries. *Curr Sports Med Rep*. 2010;9(3):176-182.
17. García-Pérez JA, Pérez-Soriano P, Llana S, Martínez-Nova A, Sánchez-Zuriaga D. Effect of overground vs treadmill running on plantar pressure: Influence of fatigue. *Gait Posture*. 2013;38(4):929-933.
18. García-Pinillos F, Cartón-Llorente A, Jaén-Carrillo D, et al. Does fatigue alter step characteristics and stiffness during running? *Gait Posture*. 2020;76:259-263.
19. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Br J Sports Med*. 2007;41(8):469-480.
20. Gross TS, Bunch RP. A mechanical model of metatarsal stress fracture during distance running*. *Am J Sports Med*. 1989;17(5):669-674.
21. Gruber AH, Helfrich P, Desai G, Paquette M. Gait Alterations from a Prolonged Run Persist After Four Minutes Segment Coordination Patterns and Variability among Prospectively Injured Runners View project Wearables View project. In: *International Society of Biomechanics/American Society of Biomechanics*. ; 2019.
22. Hanley B, Bissas A, Merlino S, Gruber AH. Most marathon runners at the 2017 IAAF World Championships were rearfoot strikers, and most did not change footstrike pattern. *J Biomech*. 2019;92:54-60.
23. Hanley B, Tucker CB, Bissas A, Merlino S, Gruber AH. Footstrike patterns and race performance in the 2017 IAAF World Championship men's 10,000 m final. *Sports Biomech*. Published online 2021.
24. Hart NH, Nimphius S, Rantalainen T, Ireland A, Siafarikas A, Newton RU. Mechanical basis of bone strength: influence of bone material, bone structure and muscle action. *J Musculoskelet Neuronal Interact*. 2017;17(3):114-139.
25. Hong Y, Wang L, Li JX, Zhou JH. Comparison of plantar loads during treadmill and overground running. *J Sci Med Sport*. 2012;15(6):554-560.

26. Hootman J, Macera C, Ainsworth B, Martin M, Addy C, Blair S. Predictors of lower extremity injury among recreationally active adults. *Clin J Sport Med.* 2002;12(2):99-106.
27. Karagounis P, Prionas G, Armenis E, Tsiganos G, Baltopoulos P. The impact of the spartathlon ultramarathon race on athletes' plantar pressure patterns. *Foot Ankle Spec.* 2009;2(4):173-178.
28. Kelsey JL, Bachrach LK, Procter-Gray E, et al. Risk factors for stress fracture among young female cross-country runners. *Med Sci Sports Exerc.* 2007;39(9):1457-1463.
29. Kim HK, Mirjalili SA, Fernandez J. Gait kinetics, kinematics, spatiotemporal and foot plantar pressure alteration in response to long-distance running: Systematic review. *Hum Mov Sci.* 2018;57:342-356.
30. Kong PW, De Heer H. Wearing the F-Scan mobile in-shoe pressure measurement system alters gait characteristics during running. *Gait Posture.* 2009;29(1):143-145.
31. Logan S, Hunter I, Hopkins JT, Feland JB, Parcell AC. Ground reaction force differences between running shoes, racing flats, and distance spikes in runners. *J Sports Sci Med.* 2010;9:147-153.
32. Matijevich ES, Branscombe LM, Scott LR, Zelik KE. Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. *PLoS One.* 2019;14(1).
33. Mayer SW, Joyner PW, Almekinders LC, Parekh SG. Stress Fractures of the Foot and Ankle in Athletes. *Sports Health.* 2014;6(6):481-491.
34. Mei Q, Gu Y, Xiang L, Baker JS, Fernandez J. Foot pronation contributes to altered lower extremity loading after long distance running. *Front Physiol.* 2019;10(MAY).
35. Messier SP, Martin DF, Mihalko SL, et al. A 2-Year prospective cohort study of overuse running injuries: the runners and injury longitudinal study (TRAILS). *Am J Sports Med.* 2018;46(9):2211-2221.
36. Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc.* 2006;38(2):323-328.
37. Nagel A, Fernholz F, Kibele C, Rosenbaum D. Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait Posture.* 2008;27(1):152-155.
38. Nunns M, Stiles V, Fulford J, Dixon S. Estimated third metatarsal bending stresses are highly susceptible to variations in bone geometry. *Footwear Sci.* 2017;9(3):127-137.

39. Nuyts L, de Brabandere A, van Rossom S, Davis J, Vanwanseele B. Machine-learned-based prediction of lower extremity overuse injuries using pressure plates. *Front Bioeng Biotechnol.* 2022;10.
40. Paquette MR, Melcher DA. Impact of a long run on injury-related biomechanics with relation to weekly mileage in trained male runners. *J Appl Biomech.* 2017;33(3):216-221.
41. Pataky TC, Caravaggi P, Savage R, Crompton RH. Regional peak plantar pressures are highly sensitive to region boundary definitions. *J Biomech.* 2008;41(12):2772-2775.
42. Pataky TC, Robinson MA, Vanrenterghem J. Region-of-interest analyses of onedimensional biomechanical trajectories: Bridging 0D and 1D theory, augmenting statistical power. *PeerJ.* 2016;2016(11).
43. Rice H, Nunns M, House C, Fallowfield J, Allsopp A, Dixon S. High medial plantar pressures during barefoot running are associated with increased risk of ankle inversion injury in Royal Marine recruits. *Gait Posture.* 2013;38(4):614-618.
44. Stokes IAF, Hutton WC, Stott JRR. Forces acting on the metatarsals during normal walking. *J Anat.* 1979;129(3):579-590.
45. Warden SJ, Davis IS, Fredericson M. Management and prevention of bone stress injuries in long-distance runners. *J Orthop Sports Phys Ther.* 2014;44(10):749-765.
46. Warden SJ, Edwards WB, Willy RW. Preventing bone stress injuries in runners with optimal workload. *Curr Osteoporos Rep.* 2021;19(3):298-307.
47. Wei Z, Zhang Z, Jiang J, Zhang Y, Wang L. Comparison of plantar loads among runners with different strike patterns. *J Sports Sci.* 2019;37(18):2152-2158.
48. Weist R, Eils E, Rosenbaum D. The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *Am J Sports Med.* 2004;32(8):1893-1898.
49. Willems TM, De Ridder R, Roosen P. The effect of a long-distance run on plantar pressure distribution during running. *Gait Posture.* 2012;35(3):405-409.
50. Williams KR, Snow R, Agruss C. Changes in distance running kinematics with fatigue. *Int J Sports Biomech.* 1991;7:138-162.
51. Willson J, Kernozek T. Plantar loading and cadence alterations with fatigue. *Med Sci Sports Exerc.* 1999;31(12):1828-1833.
52. Wilzman AR, Tenforde AS, Troy KL, et al. Medical and biomechanical risk factors for incident bone stress injury in collegiate runners: Can plantar pressure predict injury? *Orthop J Sports Med.* 2022;10(6).

CHAPTER FOUR

THIRD METATARSAL HEAD AND BASE PRESSURE DIFFERENTIALS PREDICT
METATARSAL STRESS IN COLLEGIATE CROSS-COUNTRY RUNNERS

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

Author: Kaitlyn McKibben

Contributions: Development of research question, data collection, analysis and processing,
writing, revisions and editing of manuscript

Co-Author: James Becker

Contributions: Development of research question, study design,
data processing and analysis, revisions and editing of manuscript

Manuscript Information

Kaitlyn McKibben and James Becker

The American Journal of Sports Medicine

Status of Manuscript:

☒ Prepared for submission to a peer-reviewed journal

☐ Officially submitted to a peer-reviewed journal

☐ Accepted by a peer-reviewed journal

☐ Published in a peer-reviewed journal

**Third Metatarsal Head and Base Pressure Differentials Predict Metatarsal Stress in
Collegiate Cross-country Runners**

Kaitlyn McKibben and James Becker

Department of Health and Human Development, Montana State University, Bozeman, MT USA

Corresponding Author:

Dr. James Becker

219 Herrick Hall

Department of Health & Human Development

Montana State University

Bozeman, MT 59717 USA

Email: james.becker4@montana.edu

Word Count: 4305

Abstract

Background: Metatarsal stress fractures make up almost 9% of all running-related overuse injuries. However, bone stresses are difficult to measure in clinical settings and external loads acting on the metatarsal bone may be a good surrogate measure.

Purpose/Hypothesis: To determine whether pressure beneath the metatarsal head (MP), force beneath the metatarsal head (MF), or differences in pressure beneath the head and base of the third metatarsal (HBPD) are predictive of third metatarsal bone stress. We believe that greater external loads will be predictive of greater internal bone loads.

Study Design: Cross-Sectional Study

Methods: Seventeen collegiate cross-country athletes participated in this study. Participants ran barefoot across a force plate overlaid with a plantar pressure mat. Kinetics and multisegment foot kinematics were recorded. Masks applied to plantar pressure footprints returned peak pressure and force values underneath metatarsal heads and bases. Plantar stresses, dorsal stresses and midshaft bending moments acting on the shaft of the third metatarsal were calculated using a musculoskeletal model of the metatarsals. Simple and multiple linear regression analyses were used to analyze relationships between measures of external load and model outputs.

Results: All simple and multiple linear regression models were predictive of third metatarsal bone stress ($p < 0.001$). A model with HBPD and MF as predictor variables was the best predictor of plantar stress, dorsal stress, and bending moments, accounting for 72.7%, 73.1%, and 73.0% of variance, respectively. A model with only HBPD as a predictor variable accounted for 61.7%, 61.8%, and 61.7% of variance when predicting plantar stress, dorsal stress, and bending moments.

Conclusion: Greater HBPD, peak MP, and peak MF are all predictors of greater third metatarsal plantar stress, dorsal stress, and midshaft bending moments. The best model includes HBPD and MF as predictor variables, and HBPD is the best single predictor of bone loads.

Clinical Relevance: Runners with larger pressure differentials experience higher stresses in the third metatarsal during barefoot running. Simple pressure differential measurements could be used to identify injury risk in situations where gait analysis equipment necessary for calculating metatarsal bone stress is not readily available.

Introduction

Though running is a popular activity, there is a high incidence of overuse injury with nearly half of all runners experiencing a running related injury each year.¹¹ Stress fractures make up almost 16% of these injuries.⁸ An estimated 9% of running-related stress fractures will affect the metatarsal bones,²⁰ with 80-90% occurring in the second and third metatarsals.^{9,20}

Stress fracture etiology is multifactorial, involving physiological, anatomical, and mechanical factors.³¹ One contributing mechanical mechanism is repetitive, high loading during weight bearing activities like running, where the stress applied to the metatarsals during each gait cycle causes repetitive strain. Over time, this repeated deformation results in microdamage within the bone.⁶ While some microdamage is a normal part of the cyclic remodeling process of bone and vital for proper tissue adaptation, accumulation of microdamage without proper recovery can lead to bone stress injury, and ultimately fracture.¹⁷ Runners who experience larger magnitudes of bone stress may be at a higher risk for developing injuries,⁴ and identifying large stresses could be helpful in preventing injury.

However, quantification of bone stress during movement may be difficult in clinical settings. In vivo direct measurement techniques using strain gauges and sensors implanted in or adhered to bone are the gold standard methods for accurately measuring bone stress.^{2,21} But this is highly invasive, requiring surgery and anesthetic to place material directly into bone, and not conducive for most clinical environments.^{3,18} Indirect estimates of bone stress can be obtained using finite element models or mathematical models of the metatarsals.^{1,7,10,15} While far less invasive, these models can be costly from both computational requirements and equipment perspectives. In addition to technical expertise to run the models, most modelling requires inputs of kinematic and kinetic data collected using three-dimensional motion capture or force plates, tools which are not readily available in most clinical settings.^{10,14,18} Thus, existing methods of metatarsal bone stress modeling may not have clinical utility for injury risk assessment.

A solution to this problem would require use of methods that are clinically feasible in terms of being both time and cost effective. The use of plantar pressure mapping represents one possible solution. Plantar pressure mapping equipment is less costly than force plates or a motion capture set up, and likely within budget for many clinical settings. There are numerous examples in the literature where this technology has been used to assess large cohorts of individuals in short periods,^{23,32} showing this to be a time efficient method. Most commercially available pressure mapping software allows users to identify specific regions of interest quickly and reliably.^{5,35} Using this method to calculate pressures and forces under the metatarsal heads may be sufficient to identify individuals with higher bone stresses, and thus higher risk of injury.

However, the most appropriate measures to quantify from a pressure mat remain unclear. Pressure differentials between the head and the base of the metatarsals have been suggested as

surrogate measures for bone stress.²⁸ Alternatively, either peak pressures (MP) or peak forces under metatarsal heads (MF) may be better options. If head-base pressure differentials (HBPD), MP, MF, or a combination of the three are able to predict bending moments or dorsal and plantar stresses then this would alleviate the need for expensive equipment and complicated models to identify potential injury risk in clinical settings. Therefore, the aim of this study was to determine whether MP, MF, or HBPD during the stance phase of barefoot running gait predict plantar stress, dorsal bone stress, and bending moment in the third metatarsal. We hypothesize that both greater MP and MF and greater HBPD will predict higher stresses in the third metatarsal shaft.

Methods

Participants

Seventeen collegiate cross-country athletes participated in this study (sex: 10 female, 7 male, age: 20.0 ± 1.55 years, height: 1.75 ± 0.08 m, mass: 55.05 ± 5.52 kg). All participants were highly trained runners who ran at least 20 miles per week (mean: 61.43 ± 17.01 miles per week and 5.57 ± 1.27 years running experience). Inclusion criteria included being injury free at the time of testing with no injury in the previous six months, and no history of metatarsal stress fracture. Prior to participation, all participants provided written informed consent. All protocols in this study were approved by the University's Institutional Review Board.

Protocol

After completing a five-minute treadmill warmup at a self-selected pace, participants ran barefoot across a force plate (AMTI, Watertown, MA) overlaid with a plantar pressure mat (Matscan, Tekscan Inc. Boston, MA; Figure 1). The plantar pressure mat was 50.8 by 49.9 cm

and contained 2,288 sensels with a sensel density of 1.4 sensels per cm² and maximum pressure resolution of 862 kPa. Participants completed as many trials as needed until three “good” trials were collected. A trial was considered “good” when the participant’s right foot landed in the center of the pressure mat with no visible alterations to their normal stride indicative of targeting the mat. Ground reaction forces and pressure measurements were simultaneously recorded at 1000 Hz and 400 Hz, respectively. Whole body kinematics were recorded with a 10-camera motion capture system (Motion Analysis Corp., Rohnert Park, CA) sampling at 200 Hz. Foot kinematics were quantified using the Rizzoli multi-segment foot model¹⁹. Reflective markers were placed on the hallux, and head and base of the first, second, fourth, and fifth metatarsals, navicular tuberosity, the posterior aspect, sustentaculum tali and peroneal trochlea of the calcaneus. Additional markers were placed on the sternum, seventh cervical vertebrae, and head, as well as bilaterally on the acromioclavicular joint, medial and lateral epicondyles of the humerus, styloid processes of the radius and ulna, anterior superior iliac spine, iliac crest, posterior superior iliac spine, medial and lateral femoral epicondyles, and the medial and lateral malleoli.

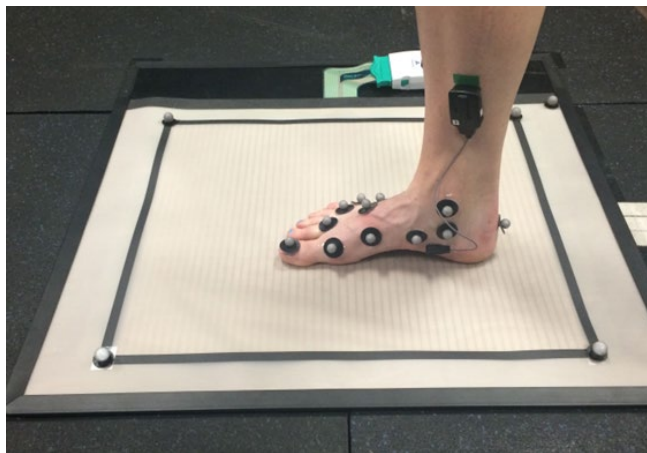


Figure 1. Force plate overlaid with a plantar pressure mat.

Data Analysis

Marker trajectories were tracked in Cortex software (Motion Analysis Corp, Rohnert Park, CA) where they were filtered with a zero-lag, lowpass Butterworth filter with a cutoff frequency of 8 Hz. Markers placed on the head and base of the metatarsal were used to determine metatarsal length. Masks were applied to peak pressure footprints in the Matscan Research software (Tekscan Inc., Boston MA) to determine peak pressure and normal force values under the third metatarsal heads and bases, toes, as well as toe lengths. Pressure differentials were calculated by subtracting the pressure at the metatarsal base from the pressure at the metatarsal head. Force values beneath the toe and metatarsal head were estimated using the pressure measurements and square area of the region masks. The percentage of whole foot force contained in each region was multiplied by ground reaction forces measured by the force plate to determine anterior-posterior and vertical ground reaction forces in each region. Plantar stresses, dorsal stresses and midshaft bending moments acting on the shaft of the third metatarsal were calculated using a musculoskeletal model, described in detail elsewhere^{10,14}, and custom Matlab code (MathWorks, Natick, MA). In brief, the model uses beam theory to estimate metatarsal loads. Ground reaction forces under the toe were used to calculate joint reaction forces at the metatarsophalangeal joint. Along with ground reaction forces beneath the metatarsal head, metatarsal length, and previously reported estimates of metatarsal radii^{14,30}, metatarsophalangeal joint reaction forces were then used to calculate axial forces, shear forces, and midshaft bending moments acting on the shaft of the metatarsal. Finally, forces, bending moments, and previously reported estimates of metatarsal cross-sectional area^{14,30} were used to estimate the tensile and compressive stresses acting at the midpoint of the metatarsal shaft. Model assumptions include assuming the toe is one segment, that flexor muscles act a single

point on the metatarsal, and kinetics and kinematics in the mediolateral direction and segment masses are negligible.^{10,14}

Statistical Analysis

Three right footprints from each participant were analyzed. All dependent variables were assessed for normality using Shapiro-Wilks tests. Plantar stress, dorsal stress, and midshaft bending moments from each trial were individually compared to HBPD, MP, and MF calculated from the corresponding footprint. Linear regressions were conducted for each comparison to determine if HBPD, MP, MF, or combinations of the three were predictive of plantar stress, dorsal stress, or midshaft bending moments in the third metatarsal. All statistical tests were performed using RStudio (Posit Software, Version 1.4.1717; Boston, MA) with significance levels set to $p \leq 0.05$.

Results

Four out of 51 trials were eliminated from analysis because the plantar pressure footprints were incomplete. Tests for normality indicated that all variables were normally distributed ($p > 0.05$). Mean and standard deviations for critical model input parameters are shown in Table 1 and all were within one standard deviation of previously reported values for these parameters.^{10,14} All proposed simple and multiple linear regression models were predictive of plantar stress, dorsal stress, and midshaft bending moments ($p < 0.001$, Table 2). A model including MF and HBPD as predictor variables, and a second model including MP, MF, and HBPD were the greatest predictors of bone load. However, while lack of fit F-tests showed no differences between the two models, regression analysis showed that MP was not a significant predictor.

Variable	Mean $\pm$ SD
Peak HBPD (KPa)	227.66 $\pm$ 53.68
Peak MP (KPa)	315.60 $\pm$ 61.52
Peak Plantar Stress (MPa)	236.23 $\pm$ 57.82
Peak Dorsal Stress (MPa)	-240.26 $\pm$ 58.28
Peak MBM (Nm)	4.14 $\pm$ 1.01
Peak MF (N)	165.04 $\pm$ 33.43

Table 1. Peak values (mean $\pm$ standard deviation). Negative stress represents compression. Positive stress represents tension.

Predictor Variables	Plantar Stress		Dorsal Stress		Midshaft Bending Moment	
	<i>P</i>	<i>R</i> ²	<i>P</i>	<i>R</i> ²	<i>P</i>	<i>R</i> ²
HBPD	< 0.001	0.617	< 0.001	0.618	< 0.001	0.617
MP	< 0.001	0.466	< 0.001	0.468	< 0.001	0.468
MF	< 0.001	0.514	< 0.001	0.519	< 0.001	0.516
MP, MF	< 0.001	0.600	< 0.001	0.605	< 0.001	0.602
HBPD, MP	< 0.001	0.604	< 0.001	0.605	< 0.001	0.606
HBPD, MF	< 0.001	0.727	< 0.001	0.731	< 0.001	0.730
HBPD, MP, MF	< 0.001	0.723	< 0.001	0.727	< 0.001	0.725

Table 2. *p* and *R*² values for simple and multiple linear regression models with different combinations of predictor variables for plantar stress, dorsal stress, and midshaft bending moments.

Discussion

The purpose of this study was to determine whether peak pressure under the metatarsal head (MP), peak force under the metatarsal head (MF), difference in peak pressure between the head and base (HBPD), or a combination of the three predicts loading in the third metatarsal. In support of our hypothesis, runners with larger peak MP, peak MF, or HBPD experienced greater peak plantar and dorsal stresses, and midshaft bending moments on the shaft of the third metatarsal. The simplest model accounting for the most variance involved MF and HBPD as predictor variables, suggesting that force, and not pressure, is a more influential cause of

metatarsal bending. While these models accounted for the most variance, the use of two different metrics as a surrogate measure could be challenging. Using either HBPD or MF as a surrogate measure would be quick and less difficult to interpret, while still being a predictor of third metatarsal bone loads.

Even though other studies have used this metatarsal model, direct comparison of results across studies is difficult due to subtle differences in model input parameters and model execution. For input parameters, peak pressure values underneath the third metatarsal head in the current study were smaller than those previously reported, most likely due to participants in the relatively smaller body mass of our study participants.²⁷ For model execution, while our third metatarsal plantar and dorsal stresses were within one standard deviation of those reported by Ellison et al.,¹⁰ the midshaft bending moments were approximately 2.5 times smaller. This discrepancy may stem from which metatarsal is being modeled and use of subject specific metatarsal dimensions. Ellison et al. examined the second metatarsal which typically experiences greater bending moments than the third metatarsal.^{14,30} They also incorporated subject-specific geometry in their metatarsal model while the current study used a similar approach to that used by Gross & Bunch who modelled the metatarsals as a hollow ellipse and Stokes et al. who used cadaveric models and scaling factors based on participant height to estimate metatarsal radii and cross-sectional area to calculate bending moments.^{14,30} Our midshaft bending moments were similar to those reported by Gross & Bunch but larger than those reported by Stokes et al., most likely because values in that study were recorded during normal walking instead of running.^{14,30} Finally, the current study, as well as the studies of Ellison et al., Gross and Bunch, and Stokes et al., all estimated metatarsal stress using a beam theory model. In all studies, the values reported

are approximately double those reported using strain gauges implanted in the actual bone.²¹ Combined, these subtle discrepancies in model inputs and execution support the suggestion of, Ellison et al. that this method of estimating metatarsal stress is most appropriate when comparing relative values between conditions within a study rather than absolute values.

The results of this study could have potential clinical benefits. Repetitive application of stresses or bending moments at high loads leads to increased strain on the bone and without sufficient recovery time can be one contributing factor to the development of bone stress injuries.¹⁷ Runners who experience abnormally large stresses within the metatarsal bone may be more susceptible to bone stress injuries and early identification of these larger stresses could be helpful in preventing injury. However, current methods of estimating metatarsal bone stress are not feasible in most clinical settings as they are either too invasive or require too much equipment and time.^{2,25} Based on results of the current study simple pressure differential measurements or force underneath the metatarsal head could be used as a screening tool for injury risk in situations where gait analysis equipment is not available, or modeling methods are not feasible. To gain useful information about patients' bone loading during running gait, a clinician would need only a plantar pressure mat to calculate pressure measurements. However, in order to utilize HBPD as a practical method of injury risk assessment, thresholds of acceptable pressure values would need to be established.

There are several considerations to be made when interpreting the results of this study. The second and third metatarsals are the most common site of stress fracture injury in runners.²⁹ This is likely due to larger amounts of bending load experienced during running combined with their slimmer shape when compared to the first metatarsal.^{12,30} This study only evaluated bone

loading in the third metatarsal because of constraints from the plantar pressure footprint. To calculate pressure differential, a mask must be placed on the head and base of the metatarsal but due to the shape of the average foot, the base of the second metatarsal does not always come in contact with the ground when running barefoot. In cases where the metatarsal base is not part of the footprint, the force beneath the metatarsal head could instead be used as a predictor of bone stress. This method could also be feasible for estimating bone load in the fifth metatarsal, a common site of stress fracture in athletic populations.¹⁶ However it is currently unclear whether larger HBPD are predictors of bone stress in the fifth metatarsal.

Certain assumptions were used to simplify the mathematical model used in this study such as assuming the metatarsal bone could be represented as a cylindrical, hollow beam. Metatarsal shape varies between individuals and while some suggest that bone mineral density is a greater determinant of metatarsal failure,²² others have found metatarsal geometry also largely contributes to both the amount and distribution of stress experienced by the bone, including estimations of bending stresses in the third metatarsals.^{13,26} While the current study provides comparison of relative stresses across participants or conditions, incorporation of subject-specific metatarsal geometry into this mathematical model would be important for obtaining estimations of true bone stress values.¹⁰ However, the need to obtain imaging for subject specific geometry may limit the clinical utility of this approach. To properly observe kinematics of individual foot segments, participants in this study ran barefoot, a scenario that is uncommon for most runners. Several studies have looked at the differences in running mechanics between different footwear conditions. Running in minimalist shoes can increase strain rates leading to significant increases in probability of failure of the second, third, and fourth metatarsals when compared to running

the same distance in a traditional shoe.¹² Barefoot running can also cause a flatter foot placement than shod running and change plantar pressure distribution,³⁴ suggesting that while third metatarsal pressure differentials are a good predictor of bone stress during barefoot running, the relationship may differ during shod running and between shoe conditions.

This study only evaluated plantar pressure and bone loading relationships after participants ran a short distance. The effects of fatigue during a long-distance run can change running gait and loading patterns. Along with changing step cadence and foot kinematics, both shorter graded exercise tests and longer marathon distance runs have been shown to increase plantar pressure distribution underneath the metatarsal region of the foot.^{24,33} Therefore, metatarsal pressure differentials at the beginning of a run may differ from differentials after fatigue has set in and may not appropriately predict metatarsal stress. Evaluation of the relationships reported in the current study under fatiguing conditions requires further investigation. Finally, participation in this study was limited to healthy runners. It is unclear if the relationship between pressure differential and bone stress still exists in participants with pathological gaits or a history of metatarsal stress injuries. This is an especially important area for future investigations to further reinforce the potential clinical applications of the stress modeling and estimation approaches described in the current study.

Conclusion

Greater peak pressure differences between the head and base of the third metatarsal predicts greater plantar stress, dorsal stress, and midshaft bending moments acting on the metatarsal shaft in healthy cross-country runners. While a slightly weaker relationship, the peak force beneath just the metatarsal head is a similar predictor of metatarsal stress and could be

useful when pressure differentials cannot be calculated. This relationship may be clinically relevant as it could be a simple measurement for injury risk assessment that can be performed when gait analysis equipment is not readily available. Future studies should determine if this relationship still exists in shod running, long-distance running, and in pathological populations, while incorporating subject-specific geometry into the metatarsal model to determine more accurate stress estimations.

References

1. Arangio GA, Beam H, Kowalczyk G, Salathé EP. Analysis of stress in the metatarsals. *Foot and Ankle Surgery*. 1998;4:123-128.
2. Arndt A, Westblad P, Ekenman I, Lundberg A. A comparison of external plantar loading and in vivo local metatarsal deformation wearing two different military boots. *Gait Posture*. 2003;18:20-26.
3. Beck T, Petit MA, Kontulainen SA. Examining the developing bone: What do we measure and how do we do it? *J Musculoskelet Neuronal Interact*. 2005;5(3):213-224.
4. Bennell K, Matheson G, Meeuwisse W, Brukner P. Risk factors for stress fractures. *Sports Med*. 1999;28(2):91-122.
5. Brenton-Rule A, Mattock J, Carroll M, et al. Reliability of the TekScan MatScan® system for the measurement of postural stability in older people with rheumatoid arthritis. *J Foot Ankle Res*. 2012;5(1).
6. Carter W C, Hayes DR, Schurman DJ. Fatigue life of compact bone - II. Effects of microstructure and density. *J Biomech*. 1976;9:211-218.
7. Chen WP, Tang FT, Ju CW. Stress distribution of the foot during mid-stance to push-off in barefoot gait: a 3-D finite element analysis. *Clinical Biomechanics*. 2001;16:614-620.
8. Chen YT, Tenforde AS, Fredericson M. Update on stress fractures in female athletes: Epidemiology, treatment, and prevention. *Curr Rev Musculoskelet Med*. 2013;6(2):173-181.
9. Chuckpaiwong B, Cook C, Pietrobon R, Nunley JA. Second metatarsal stress fracture in sport: Comparative risk factors between proximal and non-proximal locations. *Br J Sports Med*. 2007;41(8):510-514.
10. Ellison MA, Kenny M, Fulford J, Javadi A, Rice HM. Incorporating subject-specific geometry to compare metatarsal stress during running with different foot strike patterns. *J Biomech*. 2020;105.
11. Fields KB, Sykes JC, Walker KM, et al. Prevention of running injuries. *Curr Sports Med Rep*. 2010;9(3):176-182.
12. Firminger CR, Fung A, Loundagin LL, Edwards WB. Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics*. 2017;49:8-15.
13. García-Aznar JM, Bayod J, Rosas A, et al. Load transfer mechanism for different metatarsal geometries: A finite element study. *J Biomech Eng*. 2009;131(2).

14. Gross TS, Bunch RP. A mechanical model of metatarsal stress fracture during distance running*. *Am J Sports Med.* 1989;17(5):669-674.
15. Gu YD, Ren XJ, Li JS, Lake MJ, Zhang QY, Zeng YJ. Computer simulation of stress distribution in the metatarsals at different inversion landing angles using the finite element method. *Int Orthop.* 2010;34(5):669-676.
16. Hetsroni I, Nyska M, Ben-Sira D, et al. Analysis of foot structure in athletes sustaining proximal fifth metatarsal stress fracture. *Foot Ankle Int.* 2010;31(3):203-211.
17. Hughes JM, Popp KL, Yanovich R, Bouxsein ML, Matheny RW. The role of adaptive bone formation in the etiology of stress fracture. *Exp Biol Med.* 2017;242(9):897-906.
18. Koh YG, Lee JA, Lee HY, Chun HJ, Kim HJ, Kang KT. Design optimization of high tibial osteotomy plates using finite element analysis for improved biomechanical effect. *J Orthop Surg Res.* 2019;14(1).
19. Leardini A, Benedetti MG, Berti L, Bettinelli D, Natio R, Giannini S. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait Posture.* 2007;25(3):453-462.
20. Mayer SW, Joyner PW, Almekinders LC, Parekh SG. Stress Fractures of the Foot and Ankle in Athletes. *Sports Health.* 2014;6(6):481-491.
21. Milgrom C, Finestone A, Hamel A, Mandes V, Burr D, Sharkey N. A comparison of bone strain measurements at anatomically relevant sites using surface gauges versus strain gauged bone staples. *J Biomech.* 2004;37(6):947-952.
22. Muehleman C, Lidtke R, Berzins A, et al. Contributions of bone density and geometry to the strength of the human second metatarsal. *Bone.* 2000;27(5):709-714.
23. Nagel A, Fernholz F, Kibele C, Rosenbaum D. Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait Posture.* 2008;27(1):152-155.
24. Nagel A, Fernholz F, Kibele C, Rosenbaum D. Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait Posture.* 2008;27(1):152-155.
25. al Nazer R, Lanovaz J, Kawalilak C, Johnston JD, Kontulainen S. Direct in vivo strain measurements in human bone-A systematic literature review. *J Biomech.* 2012;45(1):27-40.
26. Nunns M, House C, Fallowfield J, Allsopp A, Dixon S. Biomechanical characteristics of barefoot footstrike modalities. *J Biomech.* 2013;46(15):2603-2610.

27. Nunns M, Stiles V, Fulford J, Dixon S. Estimated third metatarsal bending stresses are highly susceptible to variations in bone geometry. *Footwear Sci.* 2017;9(3):127-137.
28. Orendurff MS, Rohr ES, Segal AD, Medley JW, Green JR, Kadel NJ. Biomechanical analysis of stresses to the fifth metatarsal bone during sports maneuvers: Implications for fifth metatarsal fractures. *Physician and Sportsmedicine.* 2009;37(2):87-92.
29. Queen RM, Abbey AN, Chuckpaiwong B, Nunley JA. Plantar loading comparisons between women with a history of second metatarsal stress fractures and normal controls. *Am J Sports Med.* 2009;37(2):390-395.
30. Stokes IAF, Hutton WC, Stott JRR. Forces acting on the metatarsals during normal walking. *J Anat.* 1979;129(3):579-590.
31. Troy KL, Davis IS, Tenforde AS. A narrative review of metatarsal bone stress injury in athletic populations: Etiology, biomechanics, and management. *PM and R.* 2021;13(11):1281-1290.
32. Willems TM, De Ridder R, Roosen P. The effect of a long-distance run on plantar pressure distribution during running. *Gait Posture.* 2012;35(3):405-409.
33. Willson J, Kernozek T. Plantar loading and cadence alterations with fatigue. *Med Sci Sports Exerc.* 1999;31(12):1828-1833.
34. De Wit B, De Clercq D, Aerts P. Biomechanical analysis of the stance phase during barefoot and shod running. *J Biomech.* 2000;33:269-278.
35. Zammit G V, Menz HB, Munteanu SE. Reliability of the TekScan MatScan ® system for the measurement of plantar forces and pressures during barefoot level walking in healthy adults. *J Foot Ankle Res.* 2010;3:11.

CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

Metatarsal stress fractures are a common running-related overuse injury. Development of injury is multifactorial but due in part to repetitive loading without proper recovery time. Long-distance runners are more susceptible to overuse injury most likely because they endure higher volumes of repetitive loading.¹ Previous studies have observed increases in forefoot loading beneath the metatarsals after the completion of a long run.² However, it is unclear whether metatarsal bone stress and bending moments follow the same pattern. Additionally, there is a lack of quick, efficient methods of estimating metatarsal bone stress. Measuring bone stress requires either highly invasive methods,³ or modeling that can be time and resource intensive.⁴ Determining whether relationships exist between external loading parameters and internal stresses may be consequential in developing a clinically feasible method of estimating metatarsal bone stress and who may be at risk for injury.

The purpose of Study 1 (Chapter Three) was to determine how completion of a long-distance run affects plantar stress, dorsal stress, and midshaft bending moments in the metatarsals. Participants ran a distance equivalent to 25% of their average weekly mileage. Rather than a completely exhaustive run, this distance was chosen in an effort to better replicate the length of a runner's typical weekly long run.⁵ Results showed that peak plantar stress, peak dorsal stress, and peak bending moments were all greater in the second and third metatarsals following the run. Vertical ground reaction forces (vGRF) underneath the metatarsals were increased after the run. Specifically, vGRF was greater beneath the second, third, and fourth metatarsal heads. Post run, stresses and bending moments in the second metatarsal were

significantly greater between ~40-80% of the stance phase of gait, while stresses and bending moments were significantly greater in the third metatarsal between ~55-58% and 66-69% of stance phase. Additionally, the time of peak dorsal stress was later following the run than at the beginning of the run. These results indicate that modifications of running gait as a result of fatigue may increase metatarsal loading, especially beneath the second and third metatarsals. This may help to explain why running-related stress fracture incidence is much higher in the second and third metatarsals.

Study 2 (Chapter 4) built off of an idea by Orendurff et al. who suggested that pressures differences between the head and base of the fifth metatarsal may be a possible surrogate measure of metatarsal stress.⁶ The current study looked at the ability of a number of external loading variables, including head and base pressure differentials (HBPD), peak force beneath the metatarsal head (MF), and peak pressure beneath the metatarsal head (MP), to predict metatarsal stresses and bending moments. We examined these relationships in the third metatarsal, rather than the fifth metatarsal, because running-related stress fractures are more commonly seen in the second and third metatarsals.⁷ Results showed that greater HBPD, peak MF, and peak MP, and combinations of the three, are all predictors of greater third metatarsal plantar stress, dorsal stress, and bending moments. Of the proposed regression models, a model containing HBPD and MF as predictor variables had the best correlation and accounted for the most observed variance. A similar model that included HBPD, MF, and MP was similarly predictive of metatarsal bone loads. However, further analysis showed MP to be an insignificant predictor. This indicates that force may be a greater influence on metatarsal deformation than pressure. To effectively use this multiple regression model, a single surrogate predictor variable accounting for both HBPD and

MF would need to be established, but this would be difficult to do in a clinical setting. When looking at individual variables, the best single predictor was HBPD. However, MP was also a decent predictor of stresses and bending moments and could be used when the base of the metatarsal head is not present on the plantar pressure footprint. Results of this study suggest that external loading measures have the potential to be good surrogate measures of plantar stress, dorsal stress, and midshaft bending moments in the third metatarsal.

Together, the present studies help to further our understanding of metatarsal behavior during running. Study 1 analyzes how metatarsal stresses change as a result of a long run and results may provide further insight as to why the second and third metatarsals are most commonly affected by running-related stress fractures. Further, these results support inferences made in existing literature that increases in loading beneath the forefoot correspond with increases in metatarsals stress.^{2,8} However, bone stress is still difficult to estimate. In Study 2, pressure and force values beneath the metatarsals were shown to be predictive of the bending moments and stresses occurring in the third metatarsal during running gait. These results provide a basis for developing a potentially clinically feasible method of estimating bone stress. Future studies should continue to develop the accuracy and practicality of this method. If successful, identifying bone stress quickly and efficiently in clinic could help to identify those who are at higher risk of developing metatarsal stress fractures. For this to be a practical method, a threshold of acceptable pressure or force values would need to be established and additional research would need to be done to determine whether this same relationship applies to the other four metatarsals. It would also be of interest to see what kinematic variables predict bone stress.

The current studies have limitations that should be considered when evaluating the results. Participants in Study 2 were instructed to run barefoot so that a multisegmented marker set could be used to capture accurate metatarsal kinematics. Running barefoot is uncommon and the known influence of shoe cushioning on running gait and loading parameters could affect the relationships that were seen in the current study.⁹ While participants in Study 1 ran in shod conditions, it is unclear if the changes seen post long run would be the same in nontraditional running shoes. Additionally, participants in Study 1 completed their run on a treadmill. Most distance runners are partial to either trail or road running, and differences in terrain can affect loading parameters.¹⁰ Further, both studies involved healthy participants and it is unclear if relationships between external loading variable and metatarsal stress, and changes in metatarsal stress after a long run, extend to those with pathological gaits.

Both studies used a mathematical musculoskeletal model based to estimate metatarsal loads. This was a generalized model that scaled preexisting measures of metatarsal lengths and widths to each participant. However, metatarsals can vary in shape and model predictions can be sensitive to variations in bone geometry.¹¹ Incorporating subject-specific geometry in future studies would make this a more accurate model for metatarsal stresses and bending moments. Additionally, the model tends to overestimate stress in comparison to direct measurements and the results of this thesis agree with previous literature that the stress and bending moment values calculated with this model are better viewed as relative changes rather than absolutes.⁴

This thesis sought to investigate two questions related to metatarsal bone stress during running. Results indicate that a long run equivalent to 25% of average weekly mileage can increase stresses and bending moments in the second and third metatarsals, and that external

loading measures are predictive of stresses in the third metatarsal. Together, these results add to a body of knowledge by helping to explain a potential source of stress fracture injury risk, as well as a potential method of estimating metatarsal stress that could help to identify those who are at a higher risk for injury.

References

1. Hootman J, Macera C, Ainsworth B, Martin M, Addy C, Blair S. Predictors of lower extremity injury among recreationally active adults. *Clin J Sport Med.* . *Clin J Sport Med.* 2002;12(2):99-106.
2. Nagel A, Fernholz F, Kibele C, Rosenbaum D. Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait Posture.* 2008;27(1):152-155. doi:10.1016/j.gaitpost.2006.12.012
3. Arndt A, Ekenman I, Westblad P, Lundberg A. *Effects of Fatigue and Load Variation on Metatarsal Deformation Measured in Vivo during Barefoot Walking.* Vol 35.; 2002.
4. Ellison MA, Kenny M, Fulford J, Javadi A, Rice HM. Incorporating subject-specific geometry to compare metatarsal stress during running with different foot strike patterns. *J Biomech.* 2020;105. doi:10.1016/j.jbiomech.2020.109792
5. Paquette MR, Melcher DA. Impact of a long run on injury-related biomechanics with relation to weekly mileage in trained male runners. *J Appl Biomech.* 2017;33(3):216-221. doi:10.1123/jab.2016-0170
6. Orendurff MS, Rohr ES, Segal AD, Medley JW, Green JR, Kadel NJ. Biomechanical analysis of stresses to the fifth metatarsal bone during sports maneuvers: Implications for fifth metatarsal fractures. *Physician and Sportsmedicine.* 2009;37(2):87-92. doi:10.3810/psm.2009.06.1714
7. Chuckpaiwong B, Cook C, Pietrobon R, Nunley JA. Second metatarsal stress fracture in sport: Comparative risk factors between proximal and non-proximal locations. *Br J Sports Med.* 2007;41(8):510-514. doi:10.1136/bjism.2006.033571
8. Willems TM, De Ridder R, Roosen P. The effect of a long-distance run on plantar pressure distribution during running. *Gait Posture.* 2012;35(3):405-409. doi:10.1016/j.gaitpost.2011.10.362
9. Firminger CR, Fung A, Loundagin LL, Edwards WB. Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics.* 2017;49:8-15. doi:10.1016/j.clinbiomech.2017.08.006
10. García-Pérez JA, Pérez-Soriano P, Llana S, Martínez-Nova A, Sánchez-Zuriaga D. Effect of overground vs treadmill running on plantar pressure: Influence of fatigue. *Gait Posture.* 2013;38(4):929-933. doi:10.1016/j.gaitpost.2013.04.026
11. Nunns M, Stiles V, Fulford J, Dixon S. Estimated third metatarsal bending stresses are highly susceptible to variations in bone geometry. *Footwear Sci.* 2017;9(3):127-137. doi:10.1080/19424280.2017.1344326

REFERENCES CITED

- Al Nazer, R., Lanovaz, J., Kawalilak, C., Johnston, J. D., & Kontulainen, S. (2012). Direct in vivo strain measurements in human bone-A systematic literature review. In *Journal of Biomechanics* (Vol. 45, Issue 1, pp. 27–40). <https://doi.org/10.1016/j.jbiomech.2011.08.004>
- Alfuth, M., & Rosenbaum, D. (2011). Long distance running and acute effects on plantar foot sensitivity and plantar foot loading. *Neuroscience Letters*, 503(1), 58–62. <https://doi.org/10.1016/j.neulet.2011.08.010>
- Arangio, G. A., Beam, H., Kowalczyk, G., & Salathé, E. P. (1998). Analysis of stress in the metatarsals. *Foot and Ankle Surgery*, 4, 123–128.
- Arias-Moreno, A. J., Ito, K., & van Rietbergen, B. (2020). Accuracy of beam theory for estimating bone tissue modulus and yield stress from 3-point bending tests on rat femora. *Journal of Biomechanics*, 101. <https://doi.org/10.1016/j.jbiomech.2020.109654>
- Arndt, A., Ekenman, I., Westblad, P., & Lundberg, A. (2002). Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. In *Journal of Biomechanics* (Vol. 35).
- Arndt, A., Westblad, P., Ekenman, I., & Lundberg, A. (2003). A comparison of external plantar loading and in vivo local metatarsal deformation wearing two different military boots. *Gait and Posture*, 18, 20–26. www.elsevier.com/locate/gaitpost
- Bates, B. T., Osternig, L. R., Sawhill, J. A., & James, S. L. (1983). An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data. *Journal of Biomechanics*, 16(3), 181–191.
- Bauchau, O. A., & Craig, J. I. (2009). Euler-Bernoulli beam theory. In O. A. Bauchau & J. I. Craig (Eds.), *Structural Analysis* (pp. 173–221). Springer Netherlands. https://doi.org/10.1007/978-90-481-2516-6_5
- Beck, T., Petit, M. A., & Kontulainen, S. A. (2005). Examining the developing bone: What do we measure and how do we do it? *J. Musculoskelet Neuronal Interact*, 5(3), 213–224. <https://www.researchgate.net/publication/7590345>
- Bennell, K. L., Malcolm, S. A., Thomas, S. A., Wark, J. D., & Brukner, P. D. (1996). The incidence and distribution of stress fractures in competitive track and field athletes a twelve-month prospective study. *The American Journal of Sports Medicine*, 24(2), 211–217.
- Bennell, K., Matheson, G., Meeuwisse, W., & Brukner, P. (1999). Risk factors for stress fractures. *Sports Med*, 28(2), 91–122.

- Bishop, C., Paul, G., & Thewlis, D. (2013). The reliability, accuracy and minimal detectable difference of a multi-segment kinematic model of the foot-shoe complex. *Gait and Posture*, 37(4), 552–557. <https://doi.org/10.1016/j.gaitpost.2012.09.020>
- Bisiaux, M., & Moretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait and Posture*, 28(4), 693–698. <https://doi.org/10.1016/j.gaitpost.2008.05.009>
- Bovalino, S. P., & Kingsley, M. I. C. (2021). Foot strike patterns during overground distance running: A systematic review and meta-analysis. *Sports Medicine - Open*, 7(1). <https://doi.org/10.1186/s40798-021-00369-9>
- Brassey, C. A., Margetts, L., Kitchener, A. C., Withers, P. J., Manning, P. L., & Sellers, W. I. (2013). Finite element modelling versus classic beam theory: Comparing methods for stress estimation in a morphologically diverse sample of vertebrate long bones. *Journal of the Royal Society Interface*, 10(79). <https://doi.org/10.1098/rsif.2012.0823>
- Brené, S., Bjørnebekk, A., Åberg, E., Mathé, A. A., Olson, L., & Werme, M. (2007). Running is rewarding and antidepressive. *Physiology and Behavior*, 92(1–2), 136–140. <https://doi.org/10.1016/j.physbeh.2007.05.015>
- Brenton-Rule, A., Mattock, J., Carroll, M., Dalbeth, N., Bassett, S., Menz, H. B., & Rome, K. (2012). Reliability of the TekScan MatScan® system for the measurement of postural stability in older people with rheumatoid arthritis. *Journal of Foot and Ankle Research*, 5(1). <https://doi.org/10.1186/1757-1146-5-21>
- Brilakis, E., Kaselouris, E., Xypnitos, F., Provatidis, C. G., & Efstathopoulos, N. (2012). Effects of Foot Posture on Fifth Metatarsal Fracture Healing: A Finite Element Study. *Journal of Foot and Ankle Surgery*, 51(6), 720–728. <https://doi.org/10.1053/j.jfas.2012.08.006>
- Carter W C, Hayes, D. R., & Schurman, D. J. (1976). Fatigue life of compact bone - II. Effects of microstructure and density. *Journal of Biomechanics*, 9, 211–218.
- Cavanagh, P. R., & LaFortune, M. A. (1980). Ground reaction forces in distance running*. *Journal of Biomechanics*, 13, 397–406.
- Chan, C., & Rudins, A. (1994). Foot biomechanics during walking and running. In *Mayo Clinic Proceedings* (Vol. 69, Issue 5, pp. 448–461). [https://doi.org/10.1016/S0025-6196\(12\)61642-5](https://doi.org/10.1016/S0025-6196(12)61642-5)
- Chen, W.-P., Tang, F.-T., & Ju, C.-W. (2001). Stress distribution of the foot during mid-stance to push-off in barefoot gait: a 3-D ®finite element analysis. *Clinical Biomechanics*, 16, 614–620. www.elsevier.com/locate/clinbiomech
- Chen, Y. T., Tenforde, A. S., & Fredericson, M. (2013). Update on stress fractures in female athletes: Epidemiology, treatment, and prevention. *Current Reviews in Musculoskeletal Medicine*, 6(2), 173–181. <https://doi.org/10.1007/s12178-013-9167-x>

- Chuckpaiwong, B., Cook, C., Pietrobon, R., & Nunley, J. A. (2007). Second metatarsal stress fracture in sport: Comparative risk factors between proximal and non-proximal locations. *British Journal of Sports Medicine*, 41(8), 510–514. <https://doi.org/10.1136/bjsm.2006.033571>
- Chuckpaiwong, B., Nunley, J. A., Mall, N. A., & Queen, R. M. (2008). The effect of foot type on in-shoe plantar pressure during walking and running. *Gait and Posture*, 28(3), 405–411. <https://doi.org/10.1016/j.gaitpost.2008.01.012>
- Dai, S., Carroll, D. D., Watson, K. B., Paul, P., Carlson, S. A., & Fulton, J. E. (2015). Participation in Types of Physical Activities Among US Adults--National Health and Nutrition Examination Survey 1999-2006. *Journal of Physical Activity & Health*, 12, S128–S140. <https://doi.org/10.1123/jpah.2015-0038>
- De Cock, A., Willems, T., Witvrouw, E., Vanrenterghem, J., & De Clercq, D. (2006). A functional foot type classification with cluster analysis based on plantar pressure distribution during jogging. *Gait and Posture*, 23(3), 339–347. <https://doi.org/10.1016/j.gaitpost.2005.04.011>
- De Wit, B., De Clercq, D., & Aerts, P. (2000). Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics*, 33, 269–278.
- Dixon, S., Nunns, M., House, C., Rice, H., Mostazir, M., Stiles, V., Davey, T., Fallowfield, J., & Allsopp, A. (2019). Prospective study of biomechanical risk factors for second and third metatarsal stress fractures in military recruits. *Journal of Science and Medicine in Sport*, 22(2), 135–139. <https://doi.org/10.1016/j.jsams.2018.06.015>
- Dogan, A., Uslu, M., Aydinlioglu, A., Harman, M., & Akpinar, F. (2007). Morphometric study of the human metatarsals and phalanges. *Clinical Anatomy*, 20(2), 209–214. <https://doi.org/10.1002/ca.20348>
- Donahue, S. W., Sharkey, N. A., Modanlou, K. A., Sequeira, L. N., & Martin, R. B. (2000). *Bone Strain and Microcracks at Stress Fracture Sites in Human Metatarsals*.
- Ellison, M. A., Kenny, M., Fulford, J., Javadi, A., & Rice, H. M. (2020). Incorporating subject-specific geometry to compare metatarsal stress during running with different foot strike patterns. *Journal of Biomechanics*, 105. <https://doi.org/10.1016/j.jbiomech.2020.109792>
- Ferber, R., & Macdonald, S. (2014). *Running Mechanics and Gait Analysis*.
- Fields, K. B., Sykes, J. C., Walker, K. M., Jackson, J. C., Sykes, J., Walker, K., & Jackson, J. (2010). Prevention of running injuries. *Curr. Sports Med. Rep*, 9(3), 176–182. www.acsm-csmr.org

- Firminger, C. R., Fung, A., Loundagin, L. L., & Edwards, W. B. (2017). Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics*, 49, 8–15. <https://doi.org/10.1016/j.clinbiomech.2017.08.006>
- Fredericson, M., Jennings, F., Beaulieu, C., & Matheson, G. O. (1995). *Stress Fractures in Athletes*. <http://journals.lww.com/topicsinmri>
- García-Aznar, J. M., Bayod, J., Rosas, A., Larrainzar, R., García-Bógalo, R., Doblaré, M., & Llanos, L. F. (2009). Load transfer mechanism for different metatarsal geometries: A finite element study. *Journal of Biomechanical Engineering*, 131(2). <https://doi.org/10.1115/1.3005174>
- García-Pérez, J. A., Pérez-Soriano, P., Llana, S., Martínez-Nova, A., & Sánchez-Zuriaga, D. (2013). Effect of overground vs treadmill running on plantar pressure: Influence of fatigue. *Gait and Posture*, 38(4), 929–933. <https://doi.org/10.1016/j.gaitpost.2013.04.026>
- García-Pinillos, F., Cartón-Llorente, A., Jaén-Carrillo, D., Delgado-Floody, P., Carrasco-Alarcón, V., Martínez, C., & Roche-Seruendo, L. E. (2020). Does fatigue alter step characteristics and stiffness during running? *Gait and Posture*, 76, 259–263. <https://doi.org/10.1016/j.gaitpost.2019.12.018>
- Gross, T. S., & Bunch, R. P. (1989). A mechanical model of metatarsal stress fracture during distance running*. *The American Journal of Sports Medicine*, 17(5), 669–674.
- Gruber, A. H., Helfrich, P., Desai, G., & Paquette, M. (2019). Gait Alterations from a Prolonged Run Persist After Four Minutes Segment Coordination Patterns and Variability among Prospectively Injured Runners View project Wearables View project. *International Society of Biomechanics/American Society of Biomechanics*. <http://www.sportsci.org/resource/stats/>
- Gu, Y. D., Ren, X. J., Li, J. S., Lake, M. J., Zhang, Q. Y., & Zeng, Y. J. (2010). Computer simulation of stress distribution in the metatarsals at different inversion landing angles using the finite element method. *International Orthopaedics*, 34(5), 669–676. <https://doi.org/10.1007/s00264-009-0856-4>
- Gwani, A. S., Asari, M. A., & Ismail, Z. I. M. (2017). How the three arches of the foot intercorrelate. *Folia Morphologica (Poland)*, 76(4), 682–688. <https://doi.org/10.5603/FM.a2017.0049>
- Hadjidakis, D. J., & Androulakis, I. I. (2006). Bone remodeling. *Annals of the New York Academy of Sciences*, 1092, 385–396. <https://doi.org/10.1196/annals.1365.035>
- Hanley, B., Bissas, A., Merlino, S., & Gruber, A. H. (2019). Most marathon runners at the 2017 IAAF World Championships were rearfoot strikers, and most did not change footstrike pattern. *Journal of Biomechanics*, 92, 54–60. <https://doi.org/10.1016/j.jbiomech.2019.05.024>

- Hanley, B., Tucker, C. B., Bissas, A., Merlino, S., & Gruber, A. H. (2021). Footstrike patterns and race performance in the 2017 IAAF World Championship men's 10,000 m final. *Sports Biomechanics*. <https://doi.org/10.1080/14763141.2020.1856916>
- Hart, N. H., Nimphius, S., Rantalainen, T., Ireland, A., Siafarikas, A., & Newton, R. U. (2017). Mechanical basis of bone strength: influence of bone material, bone structure and muscle action. *J Musculoskelet Neuronal Interact*, 17(3), 114–139. <http://www.ismni.org>
- Hetsroni, I., Nyska, M., Ben-Sira, D., Mann, G., Segal, O., Maoz, G., & Ayalon, M. (2010). Analysis of foot structure in athletes sustaining proximal fifth metatarsal stress fracture. *Foot and Ankle International*, 31(3), 203–211. <https://doi.org/10.3113/FAI.2010.0203>
- Higginson, B. K. (2009). Methods of running gait analysis. In *Curr. Sports Med. Rep* (Vol. 8, Issue 3). <http://journals.lww.com/acsm-csmr>
- Hill, P. A. (1998). Bone Remodelling. *Journal of Orthodontics*, 25, 101–107.
- Hong, Y., Wang, L., Li, J. X., & Zhou, J. H. (2012). Comparison of plantar loads during treadmill and overground running. *Journal of Science and Medicine in Sport*, 15(6), 554–560. <https://doi.org/10.1016/j.jsams.2012.01.004>
- Hootman, J., Macera, C., Ainsworth, B., Martin, M., Addy, C., & Blair, S. (2002). Predictors of lower extremity injury among recreationally active adults. *Clin J Sport Med.* *Clin J Sport Med.*, 12(2), 99–106.
- Hoshaw, S. J., Fyhrie, D. P., Takano, Y., Burr1, \$ D B, & Milgroms, C. (1997). Technical note: A method suitable for in vivo measurement of bone strain in humans. *Journal of Biomechanics*, 30(5), 521–524.
- Hughes, J. M., Popp, K. L., Yanovich, R., Bouxsein, M. L., & Matheny, R. W. (2017). The role of adaptive bone formation in the etiology of stress fracture. *Experimental Biology and Medicine*, 242(9), 897–906. <https://doi.org/10.1177/1535370216661646>
- Hulteen, R. M., Smith, J. J., Morgan, P. J., Barnett, L. M., Hallal, P. C., Colyvas, K., & Lubans, D. R. (2017). Global participation in sport and leisure-time physical activities: A systematic review and meta-analysis. In *Preventive Medicine* (Vol. 95, pp. 14–25). Academic Press Inc. <https://doi.org/10.1016/j.ypmed.2016.11.027>
- Jandová, S., Sparks, M., Oleśniewicz, P., Charousek, J., Chrástková, M., & Markiewicz, J. (2018). Changes in the foot strike pattern and pressure distribution when running in minimalist and traditional sport shoes. *Medicina Dello Sport*, 71(2), 257–267. <https://doi.org/10.23736/S0025-7826.18.03029-6>
- Karagounis, P., Prionas, G., Armenis, E., Tsiganos, G., & Baltopoulos, P. (2009). The impact of the spartathlon ultramarathon race on athletes' plantar pressure patterns. *Foot & Ankle Specialist*, 2(4), 173–178. <https://doi.org/10.1177/1938640009342894>

- Kaufman, K. R., Brodine, S. K., Shaffer, R. A., Johnson, C. W., & Cullison, T. R. (1993). The Effect of Foot Structure and Range of Motion on Musculoskeletal Overuse Injuries. In *The American Journal of Sports Medicine* (Vol. 27, Issue 5).
- Kelsey, J. L., Bachrach, L. K., Procter-Gray, E., Nieves, J., Greendale, G. A., Sowers, M., Brown, B. W., Matheson, K. A., Crawford, S. L., & Cobb, K. L. (2007). Risk factors for stress fracture among young female cross-country runners. *Medicine and Science in Sports and Exercise*, 39(9), 1457–1463. <https://doi.org/10.1249/mss.0b013e318074e54b>
- Kim, H. K., Mirjalili, S. A., & Fernandez, J. (2018). Gait kinetics, kinematics, spatiotemporal and foot plantar pressure alteration in response to long-distance running: Systematic review. *Human Movement Science*, 57, 342–356. <https://doi.org/10.1016/j.humov.2017.09.012>
- Koh, Y. G., Lee, J. A., Lee, H. Y., Chun, H. J., Kim, H. J., & Kang, K. T. (2019). Design optimization of high tibial osteotomy plates using finite element analysis for improved biomechanical effect. *Journal of Orthopaedic Surgery and Research*, 14(1). <https://doi.org/10.1186/s13018-019-1269-8>
- Kong, P. W., & De Heer, H. (2009). Wearing the F-Scan mobile in-shoe pressure measurement system alters gait characteristics during running. *Gait and Posture*, 29(1), 143–145. <https://doi.org/10.1016/j.gaitpost.2008.05.018>
- Leardini, A., Benedetti, M. G., Berti, L., Bettinelli, D., Nativio, R., & Giannini, S. (2007). Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait and Posture*, 25(3), 453–462. <https://doi.org/10.1016/j.gaitpost.2006.05.017>
- Li, Y., Leong, K. F., & Gu, Y. (2019). Construction and finite element analysis of a coupled finite element model of foot and barefoot running footwear. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 233(1), 101–109. <https://doi.org/10.1177/1754337118803540>
- Logan, S., Hunter, I., Hopkins, J. T., Feland, J. B., & Parcell, A. C. (2010). Ground reaction force differences between running shoes, racing flats, and distance spikes in runners. *Journal of Sports Science and Medicine*, 9, 147–153. <http://www.jssm.org>
- Matcuk, G. R., Mahanty, S. R., Skalski, M. R., Patel, D. B., White, E. A., & Gottsegen, C. J. (2016). Stress fractures: pathophysiology, clinical presentation, imaging features, and treatment options. In *Emergency Radiology* (Vol. 23, Issue 4, pp. 365–375). Springer New York LLC. <https://doi.org/10.1007/s10140-016-1390-5>
- Matijevich, E. S., Branscombe, L. M., Scott, L. R., & Zelik, K. E. (2019). Ground reaction force metrics are not strongly correlated with tibial bone load when running across speeds and slopes: Implications for science, sport and wearable tech. *PLoS ONE*, 14(1). <https://doi.org/10.1371/journal.pone.0210000>

- Mayer, S. W., Joyner, P. W., Almekinders, L. C., & Parekh, S. G. (2014). Stress Fractures of the Foot and Ankle in Athletes. *Sports Health*, 6(6), 481–491. <https://doi.org/10.1177/1941738113486588>
- Mei, Q., Gu, Y., Xiang, L., Baker, J. S., & Fernandez, J. (2019). Foot pronation contributes to altered lower extremity loading after long distance running. *Frontiers in Physiology*, 10(MAY). <https://doi.org/10.3389/fphys.2019.00573>
- Messier, S. P., Martin, D. F., Mihalko, S. L., Ip, E., DeVita, P., Cannon, D. W., Love, M., Beringer, D., Saldana, S., Fellin, R. E., & Seay, J. F. (2018). A 2-Year prospective cohort study of overuse running injuries: the runners and injury longitudinal study (TRAILS). *The American Journal of Sports Medicine*, 46(9), 2211–2221. <https://doi.org/10.1177/0363546518773755>
- Milgrom, C., Finestone, A., Hamel, A., Mandes, V., Burr, D., & Sharkey, N. (2004). A comparison of bone strain measurements at anatomically relevant sites using surface gauges versus strain gauged bone staples. *Journal of Biomechanics*, 37(6), 947–952. <https://doi.org/10.1016/j.jbiomech.2003.10.008>
- Milgrom, C., Finestone, A., Sharkey, N., Hamel, A., Mandes, V., Burr, D., Arndt, A., Ekenman, I., Milgrom, I. C., & Physician, S. (2002). *Metatarsal Strains Are Sufficient to Cause Fatigue Fracture During Cyclic Overloading*.
- Milner, C. E., Ferber, R., Pollard, C. D., Hamill, J., & Davis, I. S. (2006). Biomechanical factors associated with tibial stress fracture in female runners. *Medicine and Science in Sports and Exercise*, 38(2), 323–328. <https://doi.org/10.1249/01.mss.0000183477.75808.92>
- Muehleman, C., Lidtke, R., Berzins, A., Becker, J. H., Shott, S., Sumner, D. R., & Scholl, W. M. (2000). Contributions of bone density and geometry to the strength of the human second metatarsal. *Bone*, 27(5), 709–714.
- Nagel, A., Fernholz, F., Kibele, C., & Rosenbaum, D. (2008a). Long distance running increases plantar pressures beneath the metatarsal heads. A barefoot walking investigation of 200 marathon runners. *Gait and Posture*, 27(1), 152–155. <https://doi.org/10.1016/j.gaitpost.2006.12.012>
- Nalla, R. K., Kinney, J. H., & Ritchie, R. O. (2003). Mechanistic fracture criteria for the failure of human cortical bone. In *Nature Materials* (Vol. 2, Issue 3, pp. 164–168). European Association for Cardio-Thoracic Surgery. <https://doi.org/10.1038/nmat832>
- Nazem, T. G., & Ackerman, K. E. (2012). The Female Athlete Triad. *Sports Health*, 4(4), 302–311. <https://doi.org/10.1177/1941738112439685>
- Nunns, M., House, C., Fallowfield, J., Allsopp, A., & Dixon, S. (2013). Biomechanical characteristics of barefoot footstrike modalities. *Journal of Biomechanics*, 46(15), 2603–2610. <https://doi.org/10.1016/j.jbiomech.2013.08.009>

- Nunns, M., Stiles, V., & Dixon, S. (2012). The effects of standard issue Royal Marine recruit footwear on risk factors associated with third metatarsal stress fractures. *Footwear Science*, 4(1), 59–70. <https://doi.org/10.1080/19424280.2012.666388>
- Nunns, M., Stiles, V., Fulford, J., & Dixon, S. (2017). Estimated third metatarsal bending stresses are highly susceptible to variations in bone geometry. *Footwear Science*, 9(3), 127–137. <https://doi.org/10.1080/19424280.2017.1344326>
- Nuyts, L., de Brabandere, A., van Rossom, S., Davis, J., & Vanwanseele, B. (2022). Machine-learned-based prediction of lower extremity overuse injuries using pressure plates. *Frontiers in Bioengineering and Biotechnology*, 10. <https://doi.org/10.3389/fbioe.2022.987118>
- Orendurff, M. S., Rohr, E. S., Segal, A. D., Medley, J. W., Green, J. R., & Kadel, N. J. (2009). Biomechanical analysis of stresses to the fifth metatarsal bone during sports maneuvers: Implications for fifth metatarsal fractures. *Physician and Sportsmedicine*, 37(2), 87–92. <https://doi.org/10.3810/psm.2009.06.1714>
- Paquette, M. R., & Melcher, D. A. (2017). Impact of a long run on injury-related biomechanics with relation to weekly mileage in trained male runners. *Journal of Applied Biomechanics*, 33(3), 216–221. <https://doi.org/10.1123/jab.2016-0170>
- Pataky, T. C., Caravaggi, P., Savage, R., & Crompton, R. H. (2008). Regional peak plantar pressures are highly sensitive to region boundary definitions. *Journal of Biomechanics*, 41(12), 2772–2775. <https://doi.org/10.1016/j.jbiomech.2008.06.029>
- Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2016). Region-of-interest analyses of onedimensional biomechanical trajectories: Bridging 0D and 1D theory, augmenting statistical power. *PeerJ*, 2016(11). <https://doi.org/10.7717/peerj.2652>
- Pedisic, Z., Shrestha, N., Kovalchik, S., Stamatakis, E., Liangruenrom, N., Grgic, J., Titze, S., Biddle, S., Bauman, A., & Oja, P. (2020). Is running associated with a lower risk of all-cause, cardiovascular and cancer mortality, and is the more the better? A systematic review and meta-analysis. *British Journal of Sports Medicine*, 54(15), 898–905.
- Pegrum, J., Dixit, V., Padhiar, N., & Nugent, I. (2014). The pathophysiology, diagnosis, and management of foot stress fractures. *Physician and Sportsmedicine*, 42(4), 87–99. <https://doi.org/10.3810/psm.2014.11.2095>
- Porter, A. K., Cuthbertson, C. C., & Evenson, K. R. (2020). Participation in specific leisure-time activities and mortality risk among U.S. adults. *Annals of Epidemiology*, 50, 27–34.e1. <https://doi.org/10.1016/j.annepidem.2020.06.006>
- Queen, R. M., Abbey, A. N., Chuckpaiwong, B., & Nunley, J. A. (2009). Plantar loading comparisons between women with a history of second metatarsal stress fractures and

- normal controls. *The American Journal of Sports Medicine*, 37(2), 390–395.
<https://doi.org/10.1177/0363546508324967>
- Rice, H., Nunns, M., House, C., Fallowfield, J., Allsopp, A., & Dixon, S. (2013). High medial plantar pressures during barefoot running are associated with increased risk of ankle inversion injury in Royal Marine recruits. *Gait and Posture*, 38(4), 614–618.
<https://doi.org/10.1016/j.gaitpost.2013.02.001>
- Rongstad, K. M., Tuetting, J., Rongstad, M., Garrels, K., & Meis, R. (2013). Fourth metatarsal base stress fractures in athletes: A case series. *Foot and Ankle International*, 34(7), 962–968. <https://doi.org/10.1177/1071100713475613>
- Rybicki, E. F., Simonen, F. A., & Weis, E. B. (1972). On the mathematical analysis of stress in the human femur. *Journal of Biomechanics*, 5, 203–215.
- Saunier, J., & Chapurlat, R. (2018). Stress fracture in athletes. In *Joint Bone Spine* (Vol. 85, Issue 3, pp. 307–310). Elsevier Masson SAS. <https://doi.org/10.1016/j.jbspin.2017.04.013>
- Selcuk, İ., Tatar, I., & Huri, E. (2019). Cadaveric anatomy and dissection in surgical training. In *Turkish Journal of Obstetrics and Gynecology* (Vol. 16, Issue 1, pp. 72–75). Turkish Society of Obstetrics and Gynecology. <https://doi.org/10.4274/tjod.galenos.2018.15931>
- Stokes, I. A. F., Hutton, W. C., & Stott, J. R. R. (1979). Forces acting on the metatarsals during normal walking. *J. Anat*, 129(3), 579–590.
- Tenforde, A. S., Sayres, L. C., McCurdy, M. L., Sainani, K. L., & Fredericson, M. (2013). Identifying sex-specific risk factors for stress fractures in adolescent runners. *Medicine and Science in Sports and Exercise*, 45(10), 1843–1851.
<https://doi.org/10.1249/MSS.0b013e3182963d75>
- Trinler, U., Schwameder, H., Baker, R., & Alexander, N. (2019). Muscle force estimation in clinical gait analysis using AnyBody and OpenSim. *Journal of Biomechanics*, 86, 55–63.
<https://doi.org/10.1016/j.jbiomech.2019.01.045>
- Troy, K. L., Davis, I. S., & Tenforde, A. S. (2021). A narrative review of metatarsal bone stress injury in athletic populations: Etiology, biomechanics, and management. *PM and R*, 13(11), 1281–1290. <https://doi.org/10.1002/pmrj.12518>
- van Gent, R. N., Siem, D., Van Middelkoop, M., Van Os, A. G., Bierma-Zeinstra, S. M. A., & Koes, B. W. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. In *British Journal of Sports Medicine* (Vol. 41, Issue 8, pp. 469–480). <https://doi.org/10.1136/bjsm.2006.033548>
- van Poppel, D., van der Worp, M., Slabbekoorn, A., van den Heuvel, S. S. P., van Middelkoop, M., Koes, B. W., Verhagen, A. P., & Scholten-Peters, G. G. M. (2021). Risk factors for

- overuse injuries in short- and long-distance running: A systematic review. *Journal of Sport and Health Science*, 10(1), 14–28. <https://doi.org/10.1016/j.jshs.2020.06.006>
- Volf, J., Novák, V., Ryženko, V., Bezouška, V., & Bláhová, M. (2021). Transducer for in bone stress and remodelling measuring. *Measurement: Sensors*, 18. <https://doi.org/10.1016/j.measen.2021.100312>
- Warden, S. J., Davis, I. S., & Fredericson, M. (2014). Management and prevention of bone stress injuries in long-distance runners. *J Orthop Sports Phys Ther.*, 44(10), 749–765. <https://doi.org/10.2519/jospt.2014.5334>
- Warden, S. J., Edwards, W. B., & Willy, R. W. (2021). Preventing bone stress injuries in runners with optimal workload. *Current Osteoporosis Reports*, 19(3), 298–307. <https://doi.org/10.1007/s11914-021-00666-y>
- Wei, Z., Zhang, Z., Jiang, J., Zhang, Y., & Wang, L. (2019). Comparison of plantar loads among runners with different strike patterns. *Journal of Sports Sciences*, 37(18), 2152–2158. <https://doi.org/10.1080/02640414.2019.1623990>
- Weist, R., Eils, E., & Rosenbaum, D. (2004). The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *The American Journal of Sports Medicine*, 32(8), 1893–1898. <https://doi.org/10.1177/0363546504265191>
- Willems, T. M., De Ridder, R., & Roosen, P. (2012). The effect of a long-distance run on plantar pressure distribution during running. *Gait and Posture*, 35(3), 405–409. <https://doi.org/10.1016/j.gaitpost.2011.10.362>
- Williams, K. R., Snow, R., & Agruss, C. (1991). Changes in distance running kinematics with fatigue. *Int J Sports Biomech*, 7, 138–162.
- Willson, J., & Kernozek, T. (1999). Plantar loading and cadence alterations with fatigue. *Med Sci Sports Exerc.*, 31(12), 1828–1833.
- Wilzman, A. R., Tenforde, A. S., Troy, K. L., Hunt, K., Fogel, N., Roche, M. D., Kraus, E., Trikha, R., Delp, S., & Fredericson, M. (2022). Medical and biomechanical risk factors for incident bone stress injury in collegiate runners: Can plantar pressure predict injury? *Orthopaedic Journal of Sports Medicine*, 10(6). <https://doi.org/10.1177/23259671221104793>
- Wolfram, U., & Schwiedrzik, J. (2016). Post-yield and failure properties of cortical bone. *BoneKEY Reports*, 5. <https://doi.org/10.1038/bonekey.2016.60>
- Wren, T. A. L., Gorton, G. E., Öunpuu, S., & Tucker, C. A. (2011). Efficacy of clinical gait analysis: A systematic review. In *Gait and Posture* (Vol. 34, Issue 2, pp. 149–153). <https://doi.org/10.1016/j.gaitpost.2011.03.027>

- Yang, P. F., Bruggemann, G.-P., & Rittweger, J. (2011). What do we currently know from in vivo bone strain measurements in humans? *Journal of Musculoskeletal and Neuronal Interaction*, 11(1), 8–20.
- Zammit, G. V., Menz, H. B., & Munteanu, S. E. (2010). Reliability of the TekScan MatScan ® system for the measurement of plantar forces and pressures during barefoot level walking in healthy adults. *Journal of Foot and Ankle Research*, 3, 11.
<http://www.jfootankleres.com/content/3/1/11>
- Zhang, Y., Awrejcewicz, J., Szymanowska, O., Shen, S., Zhao, X., Baker, J. S., & Gu, Y. (2018). Effects of severe hallux valgus on metatarsal stress and the metatarsophalangeal loading during balanced standing: A finite element analysis. *Computers in Biology and Medicine*, 97, 1–7. <https://doi.org/10.1016/j.compbimed.2018.04.010>
- Zysset, P. K., Dall'Ara, E., Varga, P., & Pahr, D. H. (2013). Finite element analysis for prediction of bone strength. *BoneKEy Reports*, 2. <https://doi.org/10.1038/bonekey.2013.120>