

2010

Medial longitudinal arch mechanics before and after a prolonged run

Elizabeth Rose Hageman
Iowa State University

Follow this and additional works at: <https://lib.dr.iastate.edu/etd>

 Part of the [Kinesiology Commons](#)

Recommended Citation

Hageman, Elizabeth Rose, "Medial longitudinal arch mechanics before and after a prolonged run" (2010). *Graduate Theses and Dissertations*. 11848.
<https://lib.dr.iastate.edu/etd/11848>

This Thesis is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

Medial longitudinal arch mechanics before and after a prolonged run

By

Elizabeth Rose Hageman

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Kinesiology (Biological Basis of Physical Activity)

Program of Study Committee:
Timothy R. Derrick, Major Professor
Jason Gillette
Gary Mirka

Iowa State University
Ames, Iowa
2010

Copyright © Elizabeth Rose Hageman, 2010. All rights reserved.

TABLE OF CONTENTS

ABSTRACT.....	iii
CHAPTER 1. GENERAL INTRODUCTION	1
Introduction to the Problem	1
Purpose and Hypotheses	5
Organization of Thesis	5
References.....	6
CHAPTER 2. LITERATURE REVIEW	10
Purpose of the Medial Longitudinal Arch	10
Structural Components of the Foot.....	11
Foot and Leg Coupling	16
Foot Type	17
<i>Classifying Foot Type and Arch Motion</i>	17
<i>Foot Rigidity and Static Predictability</i>	25
<i>Foot Type and Injuries</i>	28
External Motion Control.....	29
Changes after Long Runs/Fatigue.....	31
Summary	33
References.....	34
CHAPTER 3. MEDIAL LONGITUDINAL ARCH MECHANICS BEFORE AND AFTER A PROLONGED RUN	46
Abstract.....	46
Introduction.....	48
Methods.....	50
Results.....	54
Discussion	59
Conclusions.....	64
References.....	66
CHAPTER 4. GENERAL CONCLUSION	70
Summary	70
Recommendations for Future Research	70
COMPLETE REFERENCE LIST	72
APPENDIX A. EXTENDED LIMITATIONS.....	85
APPENDIX B. EXTENDED RESULTS	87
ACKNOWLEDGEMENTS.....	89

ABSTRACT

Collapse and reformation of the medial longitudinal arch during gait is controlled passively and actively. If either tissue group fatigues over the duration of a run, the change in arch mechanics may increase risk of running injuries. However, a 3-dimensional kinematic analysis of the medial longitudinal arch after a prolonged run has not been performed.

Additionally, rarely has arch collapse been quantified for walking and running in the same study.

PURPOSE: To compare arch mechanics before and after a 45 minute run and to compare walking and running arch deformation. **METHODS:** Thirty runners performed barefoot walking and running trials before and after a 45 minute treadmill run. Reflective markers were placed on the foot and lower limb. Arch lengthening, navicular displacement, and arch height index quantified arch motion. Arch rigidity index and dynamic arch stiffness, a new measurement, quantified resistance to collapse. **RESULTS:** There was a significant gender \times time interaction for arch rigidity index, decreasing after the run for men and increasing for women. There was no main effect for either time or gender for any other dependent variable. Walking and running, however, were significantly different for all relevant variables. Arch collapse was significantly greater for running than walking. **CONCLUSION:** The structures of the medial longitudinal arch of the foot may have adapted to the cyclical loading of the run by recruiting other muscles, or the arch may be resilient to change after a non-exhausting run. Greater arch deformation during running was likely a function of increased plantarflexion moment and ground reaction forces compared to walking.

CHAPTER 1. GENERAL INTRODUCTION

Nearly 10 million Americans run regularly (Gellman and Burns, 1996) and annual injury rates range from 19-85% (Bovens et al., 1989; Macera et al., 1989; van Gent et al., 2007). In just one mile of running, the foot contacts the ground about 1000 times (Davis et al., 2010), so if a runner logs 15 or more miles per week, he or she is exposed to at least 15,000 impacts. During contact with the ground, reaction forces are about 2.5 body weights, which is approximately twice as much as walking (Nilsson and Thorstensson, 1989). If adequate rest is not allowed between repetitive bouts of exercise, damage to bones and soft tissues may ensue. It is imperative to study foot function as it is the mediator between the ground and the body. The association between foot structure and overuse running injury risk is ambiguous, primarily because there is a plethora of measurements used to categorize foot type. Understanding the foot as a dynamic structure with changing material properties may help identify the etiology of some overuse running injuries.

Faulty mechanics at the foot/ground interface may cause injuries at the foot or elsewhere up the kinetic chain because a coupling exists between rearfoot motion and tibial rotation (Inman, 1976). Change in navicular height, one measure of medial longitudinal arch (MLA) mobility, and calcaneal in/eversion are coupled (Mathieson et al., 2004). Internal tibial rotation is coupled with eversion/pronation and knee flexion, which occurs in the first half of stance, and external tibial rotation is coupled with inversion/supination and knee extension, which occurs in the second half of stance (Markolf et al., 1976; Pohl and Buckley, 2008). If MLA collapse or pronation is prolonged during running, the extending knee will be externally rotating the tibia while the collapsing arch will be promoting internal tibial rotation. These unsynchronized events have been suggested to cause knee injuries because

they increase torsional stress at the knee (Bellchamber and van den Bogert, 2000). Although the most common overuse running injuries affect the knee (Fredericson et al., 2007; Taunton et al., 2002b), the transfer of motion between segments may be why 77% of knee injuries in runners were related to abnormal foot biomechanics (Lutter, 1980).

Although commonly modeled as a rigid segment, several studies have identified movement between the bones of the foot during walking and running (Arndt et al 2007; Nester et al., 2010; Wolf et al., 2008). One such movement is collapse and reformation of the MLA. This movement is essential as it helps absorb energy through rotation of bones and deformation of tissues, such as the plantar fascia, plantar ligaments, and muscles/tendons (Ker et al., 1987; Yoshikawa et al., 1994). As the weight of the body moves from the heel to midfoot at midstance, the MLA begins to collapse, stretching the plantar fascia and plantar ligaments. At the same time, the subtalar and other joints of the arch rotate, which is actively controlled by eccentric contraction of the triceps surae, posterior tibialis, flexor digitorum longus, and other muscles. Because of the oblique axis of the subtalar joint, internal tibial rotation also occurs. During midstance, triceps surae activity increases to cause ankle plantarflexion, which aids in MLA depression (Cheung et al., 2006). After heel rise and the commencement of propulsion, center of pressure moves over the metatarsal heads and reduces loading of the arch. Also during propulsion, the toes dorsiflex and the plantar fascia tightens as it winds around the metatarsal heads (Hicks, 1954). This increases tension within the fascia, shortening the distance between the calcaneus and metatarsals and raising the MLA—a phenomenon known as the windlass mechanism.

Dynamic MLA deformation has been quantified more often for walking than running. During walking, arch height decreases about 11 to 15% or 5.3 to 8 mm (Cashmere et al.,

1999; Cornwall and McPoil, 1999; Hunt et al., 2001; Nielsen et al., 2009) and arch length increases about 2% or 4 mm (Cashmere et al., 1999; Yang et al., 1985). During running, arch height decreases up to 10 mm (Ker et al., 1987; Nachbauer and Nigg, 1992). Comparisons between walking and running are difficult as various measurements and different references (sit versus stand) are used. Only one study compared walking and running and reported greater MLA collapse in running than walking (McPoil and Cornwall, 2007), which is reasonable considering loading and triceps surae activity are greater in running.

Besides energy absorption, other characteristics of the viscoelastic connective tissues of the MLA include greater stiffness as strain rate increases; loss of strain energy during deformation; gradual decrease in tension over time with constant or repetitive force, and; lengthening with constant or repetitive force (Nigg and Herzog, 1994, p. 117; Whiting and Zernicke, 2008, p. 90). After five contractions of the plantarflexors at 80% of maximum, tendon length increased about 5 mm and then plateaued for the next five contractions (Maganaris et al., 2002). However, daily activity is not at 80% of maximum used in Maganaris et al. (2002). Because of these tissue properties and possible material fatigue, it can be inferred that MLA stiffness will be greater during running than walking, and MLA deformation may increase after cyclical loading from a long run.

However, muscle fatigue of the arch-supporting muscles may be more responsible for increased MLA deformation after a long run. Muscles decrease bone strain on the tensile side during bending, as demonstrated during heel rise (Sharkey et al., 1995). However, if muscles become fatigued the risk for injury may increase due to increased strains, strain rate, and bending moments (Arndt et al., 2002; Yoshikawa et al., 1994). Greater pressure under the metatarsal heads and reduced pressure under the toes after a marathon and fatiguing 30

minute run may be due to fatiguing the toe flexors, which results in increased dorsiflexion (Bisiaux and Moretto, 2008; Nagel et al. 2008). Additionally, increased peak pressure under the medial midfoot after running (Weist et al., 2004; Wu et al., 2007) support that there is greater deformation of the arch, or at least deformation velocity, which may also be linked to toe flexor fatigue. After fatiguing the intrinsic foot muscles (although extrinsic muscles were not monitored to determine specificity of the exercise), navicular drop increased from sit to stand (Headlee et al., 2008). This fatigue may have been present in dynamic activity also, although it was not tested. In contrast, a 30 minute fatiguing run resulted in decreased medial midfoot pressure (Bisiaux and Moretto, 2008). Differences in plantar region definitions may account for these differences. Regardless, the effects of fatigue may alter normal running mechanics and increase risk for injury.

Static MLA measurements may not accurately predict dynamic arch motion because a high arch may deform just as much as a low arch during gait (Cashmere et al., 1999; Kaufman et al., 1999), which emphasizes the importance of dynamic foot assessments. Studies that reported high predictive values of static measurements correlated them to arch collapse at midstance of walking (Franettovich et al., 2007; McPoil and Cornwall, 2005; McPoil and Cornwall, 2007) but maximum MLA deformation occurs later in stance after heel-rise (Cashmere et al., 1999; Hunt et al., 2001; Wearing et al., 1998). Most assessments of foot type are done statically, which may partially explain why both high and low arch feet are at increased risk for the same overuse injuries (Kaufman et al., 1999; Korpelainen et al., 2001; Williams et al., 2001). On the other hand, a lack of association between foot type or navicular drop and lower limb injuries may also result from a static assessment (Barnes et al., 2008; Nakhaee et al., 2008) as a rigid or flexible arch may more accurately relate to injury

occurrence. Since overuse injuries result from dynamic activity, a dynamic assessment of foot type (e.g., flexible or rigid) may increase predictability of injury risk.

Taken together, mechanical changes at the foot likely affect other lower limb kinematics and kinetics. After a prolonged run, the MLA collapse may increase from material fatigue of the passive tissues and from decreased force production of the arch-supporting muscles, but this has yet to be investigated using 3-D motion capture. Since the majority of training is at a comfortable intensity and not an exhausting race-pace, it is probable injuries develop at lower intensities after running a few miles. Therefore, the purpose of the current study was to evaluate the changes in medial longitudinal arch mechanics before and after a 45 minute run at a comfortable pace. Specifically, changes in arch length, navicular displacement, arch height index, arch rigidity index, and quasi-arch stiffness were recorded. It was hypothesized there would be greater MLA deformation and decreased arch stiffness after the run. The secondary aim was to compare walking and running, for which it was hypothesized arch stiffness and MLA deformation would be greater during running than walking.

The organization of this thesis will first look at previous research (Ch. 2) related to foot structure, MLA function, quantifying foot type and MLA mobility, injuries associated with foot type, and changes related to the MLA after prolonged and/or fatiguing activity, specifically running. Next, a manuscript addressing some of the gaps in the literature is presented in Ch. 3. Finally, conclusions are drawn in Ch. 4.

REFERENCES

- Arndt, A., Ekenman, I., Westblad, P., and Lundberg, A. (2002). Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *Journal of Biomechanics*, 35(5), 621-8.
- Arndt, A., Wolf, P., Liu, A., Nester, C., Stacoff, A., Jones, R., Lundgren, P., and Lundberg, A. (2007). Intrinsic foot kinematics measured in vivo during the stance phase of slow running. *Journal of Biomechanics*, 40(12), 2672-2678.
- Barnes, A., Wheat, J., and Milner, C. (2008). Association between foot type and tibial stress injuries: a systematic review. *British Journal of Sports Medicine*, 42(2), 93-8.
- Bellchamber, T.L. and van den Bogert, A.J. (2000). Contributions of proximal and distal moments to axial tibial rotation during walking and running. *Journal of Biomechanics*, 33, 1397-1403.
- Bisiaux, M. and Moretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait and Posture*, 28, 693–698.
- Bovens, A.M.P, Janssen, G.M.E., Vermeer, H.G.W., Hoeberigs, J.H., Janssen, M.P.E., and Verstappen, F.T.J. (1989). Occurrence of running injuries in adults following a supervised training program. *International Journal of Sports Medicine*, 10, S186-S190.
- Cashmere, T., Smith, R., and Hunt, A. (1999). Medial longitudinal arch of the foot: Stationary versus walking measures. *Foot and Ankle International*, 20(2), 112-8.
- Cheung, J.T-M., Zhang, M., and An, K-N. (2006). Effect of Achilles tendon loading on plantar fascia tension in the standing foot. *Clinical Biomechanics*, 21, 194–203.
- Cornwall, M. and McPoil, T. (1999). Relative movement of the navicular bone during normal walking. *Foot and Ankle International*, 20, 507–512.
- Davis, I.S., Bowser, B., and Mullineaux, D. (2010). Do impacts cause running injuries? A prospective investigation. *Proceedings of the American Society of Biomechanics 34th Annual Meeting*.
- Franettovich, M., McPoil, T., Russell, T., Skardoon, G., and Vicenzino, B. (2007). The ability to predict dynamic foot posture from static measurements. *Journal of the American Podiatric Medical Association*, 97(2), 115-120.
- Fredericson, M. and Misra, A.K. (2007). Epidemiology and aetiology of marathon running injuries. *Sports Medicine*, 37(4-5), 437-439.

Gellman, R. and Burns, S. (1996). Walking aches and running pains: Injuries of the foot and ankle. *Primary Care*, 23(2): 263-80.

Headlee, D., Leonard, J., Hart, J., Ingersoll, C., and Hertel, J. (2008). Fatigue of the plantar intrinsic foot muscles increases navicular drop. *Journal of Electromyography and Kinesiology*, 18, 420-425.

Hicks, J.H. (1954). The mechanics of the foot. II. The plantar aponeurosis and the arch. *Journal of Anatomy*, 88, 25-30.

Hunt, A.E., Smith, R.M., Torode, M, and Keenan, A.M. (2001). Inter-segment foot motion and ground reaction forces over the stance phase of walking. *Clinical Biomechanics (Bristol, Avon)*, 16, 592-600.

Inman, V.T. (1976). *The Joints of the Ankle*. Baltimore: Williams and Wilkins.

Kaufman, K.R., Brodine, S.K., Shaffer, R.A., Johnson, C.W., and Cullison, T.R. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. *American Journal of Sports Medicine*, 27(5), 585-593.

Ker, R., Bennett, M., Bibby, S.R., Kester, R.C., and Alexander, R. (1987). The spring in the arch of the human foot. *Nature*, 325, 147-49.

Korpelainen, R., Orava, S., Karpakka, J., Siira, P., and Hulkko, A. (2001). Risk factors for recurrent stress fractures in athletes. *American Journal of Sports Medicine*, 29, 304-10.

Lutter, L.D. (1980). Foot-related knee problems in the long distance runner. *Foot and Ankle*, 1, 112-116.

Macera, C.A., Pate, R.R., Powell, K.E., Jackson, K.L., Kendrick, J.S., and Craven, T.E. (1989). Predicting lower-extremity injuries among habitual runners. *Archives of Internal Medicine*, 149(11), 2565-2568.

Markolf, K.L., Mensch, J.S., and Amstutz, H.C. (1976). Stiffness and laxity of the knee—the contributions of the supporting structures. A quantitative in vitro study. *Journal of Bone and Joint Surgery (America)*, 5, 583-594.

Mathieson, I., Upton, D., and Prior, T.D. (2004). Examining the validity of selected measures of foot type: a preliminary study. *Journal of the American Podiatric Medical Association*, 94(3), 275-281.

McPoil, T. and Cornwall, M. (2005). Use of the longitudinal arch angle to predict dynamic foot posture in walking. *Journal of the American Podiatric Medical Association*, 95(2), 114-120.

- McPoil, T. and Cornwall, M. (2007). Prediction of dynamic foot posture during running using the longitudinal arch angle. *Journal of the American Podiatric Medicine Association*, 97(2), 102-107.
- Nachbauer, W. and Nigg, B.M. (1992). Effects of arch height of the foot on ground reaction forces in running. *Medicine in Science and Sports Medicine*, 24(11), 1264-9.
- Nagel, A., Fernholz, F., Kibele, C., and Rosenbaum, D. (2008). 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.
- Nakhaee, Z., Rahimi, A., Abaee, M., Rezasoltani, A. and Kalantari, K. K. (2008). The relationship between the height of the medial longitudinal arch (MLA) and the ankle and knee injuries in professional runners. *Foot (Edinburgh, Scotland)*, 18(2), 84-90.
- Nester, C.J., Liu, A.M., Ward, E., Howard, D., Cocheba, J., and Derrick, R. (2010). Error in the description of foot kinematics due to violation of rigid body assumptions. *Journal of Biomechanics*, 43(4), 666-672.
- Nielsen, R., Rathleff, M., Simonsen, O., and Langberg, H. (2009). Determination of normal values for navicular drop during walking: A new model correcting for foot length and gender. *Journal of Foot and Ankle Research*, 2, 12-18.
- Nigg, B.M. and Herzog, W. (Eds.). (1994). *Biomechanics of the Musculoskeletal System*. West Sussex, England: John Wiley and Sons, p. 117.
- Nilsson, J. and Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica Scandinavica*, 136(2), 217-227.
- Pohl, M.B. and Buckley J.G. (2008). Changes in foot and shank coupling due to alterations in foot strike pattern during running. *Clinical Biomechanics*, 23, 334-41.
- Sharkey, N. A., Ferris, L., Smith, T. S., and Matthews, D. K. (1995). Strain and loading of the second metatarsal during heel-lift. *Journal of Bone and Joint Surgery (America)*, 77(7), 1050-7.
- Sharkey, N.A., Donahue, S.W., and Ferris, L. (1999). Biomechanical consequences of plantar fascial release or rupture during gait. Part II: Alterations in forefoot loading. *Foot and Ankle International*, 20(2), 86-96.
- Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., and Lloyd-Smith, D.R. (2002a). Plantar fasciitis: A retrospective analysis of 267 cases. *Physical Therapy in Sports*, 3, 57-65.

Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R., and Zumbo, B.D. (2002b). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, 36, 95-101.

van Gent, R.N., Siem, D., van Middelkoop, M., van Os, A.G., Bierma-Zeinstra, S.M.A., Koes, B.W., et al. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *British Journal of Sports Medicine*, 41(8), 469-80.

Wearing, S.C., Urry, S., Perlman, P., Dubois, P., and Smeathers, J. (1999). Serial measurement of calcaneal pitch during midstance. *Journal of the American Podiatric Medical Association*, 89(4), 188-93.

Wearing, S.C., Urry, S., Perlman, P., Smeathers, J., and Dubois, P. (1998). Sagittal plane motion of the human arch during gait: A videofluoroscopic analysis. *Foot and Ankle International*, 19(11), 738-42.

Weist, R., Eils, E., and Rosenbaum, D. (2004). The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *American Journal of Sports Medicine*, 32(8), 1893-98.

Whiting, W. and Zernicke, R. 2008. *Biomechanics of musculoskeletal injury* (2nd ed). United States of America: Human Kinetics, p. 90.

Wolf, P., Stacoff, A., Liu, A., Nester, C., Arndt, A., Lundberg, A., and Stuessi, E. (2008). Functional units of the human foot. *Gait and Posture*, 28, 434-441.

Wu, W.L., Chang, J.J., Wu, J.H., Guo, L.Y., and Lin, H.T. (2007). EMG and Plantar Pressure Patterns after Prolonged Running. *Biomedical Engineering: Applications, Basis and Communications*, 19(6), 383-388.

Yang, S.M., Kayano, J., Norimatsu, T. Fujita, M., Matsusaka, N., and Suzuki, R. (1985). Dynamic changes of the arches of the foot during walking, in: *Biomechanics IX-A*, Winter, D.A., Norman, R.W., Wells, R.P., Hayes, K.C., and Patla, A.E. (Eds.). Champaign, IL: Human Kinetics Publishers, pp. 417-422.

Yoshikawa, T., Mori, S., Santiesteban, A.J., Sun, T.C., Hafstad, E., Chen, J., and Burr, D.B. (1994). The effects of muscle fatigue on bone strain. *Journal of Experimental Biology*, 188, 217-233.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Purpose of the Medial Longitudinal Arch

The purpose of the medial longitudinal arch (MLA) is threefold: to provide stability, absorb shock/store energy, and generate and transfer energy. The unique shape and alignment of the tarsal bones, along with multiple ligaments and aponeuroses, provide gradations of MLA stability. In the supinated posture, which occurs at both foot contact and propulsion, a more rigid configuration of the bones and angle of pull of the Achilles tendon create a more effective lever at propulsion (Elftman, 1960). Rigidity is created by the oblique calcaneocuboid and talonavicular axes being nonparallel. A more flexible alignment of bones (calcaneocuboid and talonavicular axes are parallel) during pronation near midstance, allows energy absorption and transfer between the rearfoot and forefoot (Elftman, 1960; Erdemir et al., 2004; Kirby, 2000).

Shock absorption and force attenuation occurs through MLA deformation and pronation (Hamill and Knutzen, 1995, pp. 212-213; Ker et al., 1987; Kirby, 2000; Ogon et al., 1999). For example, impact loading increased when natural pronation was hindered during running, which emphasizes the role of the MLA in shock absorption (Perry and Lafortune, 1995).

While lower limb muscles need to work synergistically during walking and running, a large quantity of energy is stored elastically in the MLA, leg, and other viscoelastic structures, with 52 to 60% of work done by tendons (Ker et al., 1987; Voigt et al., 1995). It has been estimated that 35 J and 17 J of elastic strain energy is stored in the Achilles tendon and MLA ligaments, respectively, during running (Ker et al., 1987). In the first part of

stance, energy absorption occurs and in the second half, energy is transferred from the rearfoot to forefoot (Erdemir et al., 2004).

2.2 Structural Components of the Foot

The foot is undoubtedly complex, composed of 26 uniquely shaped bones, 30 joints, over 100 ligaments, and 23 intrinsic and extrinsic muscles (Hamill and Knutzen, 2003, p. 207). The medial longitudinal arch, the most prominent and arguably the most important arch of the foot, is composed of the calcaneus, talus, navicular, cuboid, three cuneiforms, and the first three metatarsals (Hamill and Knutzen, 2003, p. 212). The navicular is considered the keystone of the MLA.

For simplicity, many researchers model the foot as a rigid body for calculating inverse dynamics, but it is highly dynamic and should be grouped into different segments, although there is no consensus. By inserting bone pins into several bones, sagittal plane rotations during walking and slow running were greatest between the cuboid and fifth metatarsal while the talonavicular joint showed the greatest frontal and transverse plane motion (Wolf et al., 2008). Two pairs of bones, the navicular and cuboid, and the medial cuneiform and first metatarsal, were considered rigid segments because they rotated in the same direction. Separating the navicular and medial cuneiform into different segments is logical as 10° of flexion occurred between these bones during slow running (Arndt et al., 2007). Wolf et al. (2008) suggested partitioning the foot into four segments: calcaneus, navicular-cuboid, fifth metatarsal, and medial cuneiform-first metatarsal. Recently an in vitro study came to similar conclusions, suggesting three segments for the mid- and forefoot: navicular-cuboid, cuneiforms-first through third metatarsals, and fourth-fifth metatarsals

(Nester et al., 2010). Partitioning the foot into these appropriate segments will allow for more valid assessments of MLA function and, in turn, more accurate injury predictions.

Connecting the multiple bones are ligaments and aponeuroses. The plantar fascia originates on the posteromedial tuberosity of the calcaneus and inserts on the proximal phalanges (Riegger, 1988). It is paramount in MLA integrity, accounting for 25% of arch stiffness (Huang et al., 1993), and it aids in transfer of load from the rearfoot to forefoot (Erdemir et al., 2004).

During propulsion as the toes dorsiflex and ankle plantarflexes, the plantar fascia tightens as it winds around the metatarsal heads (Hicks, 1954). This increases tension within the fascia, shortening the distance between the calcaneus and metatarsal and raising the MLA—a phenomenon known as the windlass mechanism. After sectioning the plantar fascia, arch length increases, arch height decreases, load is not transferred effectively to the forefoot, and resupination does not occur (Sharkey et al., 1999; Thordarson et al., 1998; Ward et al., 2003).

Tension develops in the fascia as the foot is loaded and is approximately twice as high for running versus walking (Giddings et al., 2000). Simulated walking in cadaver feet showed plantar fascia tension increased until late stance, which also corresponded to peak vertical ground reaction forces and peak axial strains in the second and fifth metatarsals (Donahue and Sharkey, 1999; Erdemir et al., 2004). This force was well correlated to Achilles tendon force, which may support why arch lengthening corresponded to triceps surae activity (Kayano, 1986).

Fascia tension is greater in low arch feet, which increases the risk of microdamage (Pohl et al., 2009; Taunton et al., 2002), but high arch feet may also be at increased risk for

fasciitis (Taunton et al., 2002). Dynamically, Taunton et al., (2002) identified over half of the plantar fasciitis patients overpronated during walking while another study reported no difference in MLA motion between plantar fasciitis and control groups (Wearing et al., 2004). In either case, excessive arch lengthening may increase stress, leading to injury.

Plantar ligaments complement the arch-supporting role of the plantar aponeurosis. The long plantar ligament originates on the calcaneus and inserts on the cuboid and second through fourth metatarsal heads (Hamill and Knutzen, 2003, p. 432). The long and short (calcaneocuboid) plantar ligaments were the second most important passive structures in supporting the MLA (Huang et al., 1993). Smaller contributions came from the spring (calcaneonavicular) ligament. Collectively, 37% of static MLA stiffness was accounted for by the plantar fascia, long and short plantar ligaments, and spring ligament as demonstrated *in vitro* (Huang et al., 1993). However, 63% of static arch stiffness was retained after sectioning all four tissues, emphasizing the contributions of muscles, bone alignment, and other ligaments.

Similar to the plantar fascia, tension in the plantar ligaments is doubled in running versus walking (Giddings et al., 2000). Peak loading of the Achilles tendon, fascia, and plantar ligaments all occurred at about 70% of stance during walking and 60% during running (Giddings et al., 2000), which corresponds to maximum MLA deformation (Caravaggi et al., 2010; Cashmere et al., 1999; Hunt et al., 2001; Wearing et al., 1998; Wearing et al., 1999). This suggests a relationship between peak tension and MLA collapse during gait.

The connective tissues of the MLA (plantar fascia, ligaments, and muscles/tendons) are viscoelastic (Whiting and Zernicke, 2008, p. 115). One defining characteristic of

viscoelasticity is increased stiffness as strain rate increases (Whiting and Zernicke, 2008, p. 90). Therefore, it can be inferred that MLA stiffness would be greater during running than walking. Additionally, Gefen (2003) found plantar fascia strain rate varied during walking, so stiffness values may vary during stance. Since the connective tissues are not perfectly elastic, some stored strain energy is lost as heat during deformation (Whiting and Zernicke, 2008, p. 91). In the force relaxation response, force rapidly decreases after loading (viscous component) and then plateaus (elastic component) with time and/or repetitive cycles (Nigg and Herzog, 1994, p. 117). Similarly, creep is a gradual lengthening of a tissue with constant or repetitive force. Because of these tissue properties, the cyclical loading that occurs during a prolonged run may cause greater MLA deformation toward the end of the run.

Eleven intrinsic muscles that do not cross the ankle joint and 12 extrinsic muscles are housed in the foot (Hamill and Knutzen, 2003, p. 214). Aside from enabling movement, muscles serve multiple functions, such as decreasing bone strain on the tensile side during bending (Sharkey et al., 1995). For example, plantar flexors of the toes (e.g., flexor digitorum longus) partially decrease strain and bending moments at simulated heel rise (Sharkey et al., 1995). Through complex modeling, Salathe and Arangio (2002) showed the extrinsic muscles of the foot also help decrease tension in the ligaments and plantar fascia. Additionally, muscles and other soft tissues help dissipate energy from collision with the ground (Zelik and Kuo, 2010; Yoshikawa et al., 1994). Therefore, if the toe plantar flexors become fatigued during a run, injury risk may increase.

Multiple muscles and tendons pass through the MLA and provide dynamic support, such as tibialis anterior, posterior tibialis, peroneus longus, flexor hallucis longus, flexor digitorum longus, and other intrinsic muscles, but posterior tibialis (i.e., tibialis posterior)

likely contributes most to dynamic stability (Basmajian and Stecko, 1963; Kaye and Jahss, 1991; Mann and Inman, 1964). Posterior tibialis, an extrinsic muscle, originates on the posterior distal third of the tibia, wraps under the medial malleolus, and inserts on multiple tarsal bones, causing inversion and plantarflexion (Semple et al., 2009). During walking, two prominent EMG bursts are observed at heel strike and midstance, but during running, only one burst is evident during stance phase (Murley et al., 2009a; Reber et al., 1993). The importance of posterior tibialis is highlighted by the following: greater EMG amplitude during walking and running in individuals with flat feet (Murley et al., 2009b); anti-pronation taping decreasing EMG amplitude 21 to 45% in barefoot walking (Franettovich et al., 2008); flattening of the MLA after posterior tibialis rupture (Geideman and Johnson, 2000); and posterior tibialis tendon dysfunction being the leading cause of adult-acquired flatfoot (Ringleb et al., 2007).

Plantarflexion is dominated by the soleus and gastrocnemius during gait, providing an estimated 93% of sagittal ankle joint torque (Perry, 1992). EMG during walking shows peak activation around midstance (Murley et al., 2009a), which slightly precedes peak ankle plantarflexion moment around 75% of stance (Hamill and Knutzen, 2003, p. 414). The attachment of the soleus and gastrocnemius on the medial side of the subtalar axis lend themselves to being supinators as well (Mann and Inman, 1964), which may be why plantarflexion torque and triceps surae strength were diminished in excessive pronators (Hintermann and Nigg, 1998; Snook, 2001).

Intrinsic foot muscles were originally thought to be silent during static standing (Mann and Inman, 1964), but navicular drop increased after a nerve block injection and fatiguing protocol, suggesting intrinsic muscle contribution during static stance (Fiolkowski

et al., 2003; Headlee et al., 2008). Dynamically, the smaller intrinsic muscles are shown to be active at heel rise and re-supination (Mann and Inman, 1964).

2.3 Foot and Leg Coupling

Movement of the foot and leg are coupled through the ankle joint complex. During walking the leg may dictate foot motion, but during running the direction of power flow ($\text{power} = \omega_{\text{segment}} * \text{Moment}_{\text{joint}}$) between segments was unclear (Bellchamber and van den Bogert, 2000). Statically placing the foot in typical in/eversion postures experienced during gait, change in navicular height was highly correlated ($r=0.80$) with calcaneal movement (Mathieson et al., 2004). However, the imperfect correlation supports the calcaneus and midtarsal bones being modeled as separate segments (Nester et al., 2010; Wolf et al., 2008) and explains why MLA collapse is lowest well after midstance of walking while maximum pronation occurs at approximately 38% of stance (Caravaggi et al., 2010; Cashmere et al., 1999; Hunt et al., 2001; McPoil and Cornwall, 1994; Wearing et al., 1998; Wearing et al., 1999). Eversion/pronation (calcaneal eversion, ankle dorsiflexion, and forefoot abduction (Ferber et al., 2009)) are coupled with internal tibial rotation and knee flexion, and inversion/supination are coupled with external tibial rotation and knee extension (Bellchamber and van den Bogert, 2000; Markolf et al., 1976; Nigg et al., 1993; Pohl and Buckley, 2008). This strong relationship of rearfoot and tibial rotation coupling during running is maintained despite foot strike style during running (Pohl and Buckley, 2008).

If MLA collapse or pronation is prolonged during gait, an extending knee will be forcing external tibial rotation while a collapsed arch will be promoting internal tibial rotation. Excessive and delayed pronation is associated with plantar fasciitis, Achilles

tendonitis, tibialis posterior-related overuse syndromes, medial tibial stress syndrome, and hallux valgus (Hintermann and Nigg, 1998; Jam, 2006). Excessive internal tibial rotation may lead to knee pain resulting from torsional forces (Bellchamber and van den Bogert, 2000).

2.4 Foot Type

2.4.1 Classifying Foot Type and Arch Motion. Classifying foot type and quantifying MLA mobility is multimodal. However, an accurate assessment is critical as different injuries are associated with foot type and may influence foot and leg coupling. Common approaches include visual non-quantitative inspection, footprint analysis, anthropometrics, radiographs, fluoroscopy, intracortical bone pins, and motion capture analysis. While radiographs and fluoroscopy are more accurate, radiographs are limited to only capturing static alignment and current fluoroscopy gait studies of the foot are only 2-D. Reflective markers placed on the skin for motion analysis can move 3.4 to 4.3 mm over proximal foot locations, such as the navicular tuberosity and medial malleolus (Maslen and Ackland, 1994; Tranberg and Karlsson, 1998). Intracortical bone pins in vivo cannot be used in the United States and are limited by pain caused, which may result in slight changes in gait patterns.

Another hindrance of comparing dynamic foot measurements, besides the various measurements, is lack of consensus whether sitting or standing foot posture should be the reference. This discrepancy, prominently due to load differences on the foot, makes comparison difficult as it is known the MLA deforms more with increasing load (Billis et al., 2007; Huang et al., 1993; McPoil and Cornwall, 2007; McPoil et al., 2008a; McPoil et al., 2009; Wearing et al., 1998).

2.4.1.1 Radiographic Measurements. Radiographic measurements used during walking include calcaneal inclination angle and calcaneal-first metatarsal angle. Both angles have intraclass correlation coefficients (ICCs) ≥ 0.97 (Wearing et al., 1998; Wearing et al., 1999). Calcaneal inclination angle, also called calcaneal pitch, is the sagittal plane angle from the supporting surface to the tangent on the inferior calcaneus (Simkin et al., 1989). During walking, calcaneal inclination angle decreased from about 25° to 12° , demonstrating a mobile MLA (Wearing et al., 1999). The calcaneal-first metatarsal angle is the angle subtended by the metatarsal declination angle and calcaneal inclination (Saltzman et al., 1995). Using fluoroscopy, nine females showed an increase in calcaneal-first metatarsal angle ranged from 120° to 144° during walking (Wearing et al., 1998). Both studies noted the arch was lowest after heel-rise (Wearing et al., 1998; Wearing et al., 1999). Because we do not have access to radiographs or fluoroscopy and radiographs only measure static foot posture, they will not be used in the current study.

2.4.1.2 Motion Capture/Clinical Measurements. Arch height is defined differently by many scientists. Williams and McClay (2000) defined it as the vertical dorsum height from the floor at 50% of total foot length. Intrarater ICCs for both static and dynamic (walking and jogging) dorsal arch height were ≥ 0.92 , while interrater ICCs were 0.93-0.97 for static and 0.86 for dynamic (Franettovich et al., 2007; McPoil et al., 2008b).

Arch height was defined differently as the perpendicular distance from the navicular tuberosity to a line connecting the first metatarsal head and posterior or medial calcaneus (Cashmere et al., 1999; Hunt et al., 2001). The definition by Hunt et al. (2001) is synonymous to navicular height used in the current study. During walking, arch height decreased 11 to 15% to its minimum at 74 to 85% of stance (Cashmere et al., 1999; Hunt et

al., 2001). Hunt et al. (2001) used standing as the reference height and Cashmere et al. (1999) used sitting, which may explain why the latter found a greater deformation (15%) compared to the former (11%). These deformations are approximately equivalent to a 4 mm change for a 30 mm arch height. As may be expected based on foot segments proposed earlier, change in arch height during walking closely resembled forefoot sagittal plane motion (Hunt et al., 2001).

Other measurements of arch height go from the floor to either the navicular tuberosity, the highest point along the soft tissue medial column of the foot, or the talar neck (Huang et al., 1993; Nachbauer and Nigg, 1992; Razeghi and Batt, 2002).

Different methods to measure vertical arch deformation during running have been used. With a reflective marker on the shoe above the intermediate cuneiform, which is approximately 50% of foot length (McPoil et al., 2009) and thus similar to dorsal arch height, MLA collapse ranged from 1 to 8 mm relative to static standing when running at 4 m/s (Nachbauer and Nigg, 1992). Running barefoot at 4 to 7 m/s, the MLA (identified by marks on the navicular and talus) lowered up to 10 mm relative to an unloaded foot (Ker et al., 1987).

Generally, arch height decreases concurrently with increasing load. From non-weightbearing to standing, dorsal arch height decreased 10-13 mm, with men showing greater decrease than women (although less than 1 mm) (McPoil et al., 2008a; McPoil et al., 2009). As static load increased from 230 to 690 N *in vitro*, arch height increased from 2.1 mm to 3.3 mm (Huang et al., 1993). Another *in vitro* came to similar conclusions that arch height increased as both vertical load and triceps surae muscle activity increased (Cheung et al., 2006). Navicular drop, or lowering of the navicular bone (discussed next), progressively

increased from sitting to standing to single-leg standing (Billis et al., 2007). Despite different methods and only one participant, arch height may decrease as running velocity increases (Ker et al., 1987), and it is known ground reaction forces increase as velocity increases. However, comparisons across studies are difficult because different definitions of arch height, reference heights, and methods are used.

Brody (1982) attempted to describe midfoot mobility by navicular drop (ND), defined as change in height of the navicular tuberosity from seated subtalar neutral to standing. While high intrarater reliability has been reported, interrater reliability is only poor to moderate (Sell et al., 1994). Typical ranges reported for sit-to-stand range from 5 to 11 mm (Bandholm et al., 2008; Billis et al., 2007; Brody, 1982; Fiolkowski et al., 2003; Headlee et al., 2008; Snook, 2001). Navicular drop of 10 to 15 mm defines a low arch, and ≤ 4 mm defines a high arch (Brody, 1982; Loudon et al., 1996; Michelson et al., 2003). From sitting to single-leg stance, ND was 4.5 mm greater than traditional sit-to-stand ND and may be as high as 13.4 mm during walking (mean: 5.3 ± 1.7 mm) (Billis et al., 2007; Nielsen et al., 2009).

Navicular drop increased 3 mm after a nerve block injection that affected intrinsic foot muscles and 1.8 mm after fatiguing intrinsic muscles (Fiolkowski et al., 2003; Headlee et al., 2008). This was accompanied by a median frequency shift of 16.6% of the abductor hallucis, an intrinsic muscle. The two prior studies allege that muscles, not just passive tissues, help support the arch during static stance. However, both studies neglected to monitor extrinsic foot muscles so it cannot be certain they were not also affected.

Injuries have been associated with increased ND. Navicular drop was greater in individuals with running injuries, medial tibial stress syndrome, and anterior cruciate ligament ruptures (Bandholm et al., 2008; Beckett et al., 1992; Bennett et al., 2001; Nakhaee

et al., 2008). However, those four studies were retrospective, which does not clarify cause and effect. One prospective study reported no association between ND and development of medial tibial stress syndrome in high school cross country runners, indicating that greater ND may be a result of medial tibial stress syndrome and not the cause (Plisky et al., 2007).

Limitations of ND include only measuring sagittal motion but the navicular moves medially as well, and ND may be influenced by foot length (Billis et al., 2007; Cornwall and McPoil, 1999; Nielsen et al., 2009; Vinicombe et al., 2001). For every 1 cm increase in foot length, walking ND increased 0.40 mm for men and 0.31 mm for women (Nielsen et al., 2009). However, walking ND and foot length correlation was low, so a longer foot minimally explained the magnitude of arch collapse.

Related to ND, navicular drift was first proposed by Menz (1998) as the medial-lateral movement of the navicular. Low intra- and interrater ICCs were reported for navicular drift, ranging from 0.31 to 0.62 (Vinicombe et al., 2001). Mean navicular drift for healthy participants was 7 ± 3 mm (from subtalar neutral standing to single-leg standing) (Vinicombe et al., 2001). With the knee flexed 30° to replicate knee angle at foot-contact during running, Billis et al. (2007) noted navicular drift increased from double-leg stance to single-leg stance as load increased (10.1 to 14.1 mm). This complements the findings that arch height decreases with increasing load.

Accounting for 3-D movement of the navicular, Cornwall and McPoil (1999) found navicular excursion was 8 ± 3 mm during walking in relation to resting standing posture. This is much more than walking ND reported by Nielsen et al. (2009) considering the latter used seated navicular height as their reference and the MLA lowers from sit to stand.

Arch length described by Cashmere et al. (1999) is the length between the first metatarsal head and posterior calcaneus. During walking, arch length increased 2% compared to seated length (Cashmere et al., 1999). This is equivalent to 4 mm for a 20 cm arch length, which is similar to 4 mm lengthening observed by Yang et al. (1985), although Yang et al. used standing as the reference length. In both studies, peak lengthening occurred at 20 to 35% of stance and remained relatively constant until 80 to 90% of stance when it rapidly shortened (Cashmere et al., 1999; Yang et al., 1985). Using fluoroscopy, Gefen (2003) noted plantar fascia length increased 9 to 12% during slow walking compared to plantar fascia length at heel contact. A more recent estimate of plantar fascia strain was 2.9 to 4.6% for walking speeds up to about 2 m/s compared to a neutral, unloaded foot (Caravaggi et al., 2010). This seems more reasonable than 9 to 12% as non-detrimental tendon strain occurs up to 4% (Kastelic and Baer, 1980). With too much lengthening, plantar fascia tension may increase and possibly lead to plantar fasciitis.

Kayano (1986) observed that the arch lengthened until foot flat as vertical ground reaction force increased, then shortened, and slightly lengthened again when tricep surae muscles were activated. During walking, the first vertical ground reaction force peak occurs at about 20% of stance and the second at about 78% (Hunt et al., 2001). These results indicate that MLA deformation may be related to ground reaction forces and/or ankle joint moment, which is substantiated by arch height decreasing as loading increases, discussed earlier.

It seems logical, and has been previously proposed (Nielsen et al., 2009), that MLA collapse be normalized, which the two following measurements (arch height index and bony arch index) achieve. Arch height (dorsal height at 50% total foot length) divided by truncated

foot length (calcaneus to the first metatarsophalangeal joint) yields arch height ratio, or more commonly called arch height index (AHI) (Williams and McClay, 2000). Perhaps it is appropriate and easier to use full foot length instead of truncated as long as toe deformities are not present (McPoil et al., 2008b). For both static and dynamic AHI, intrarater ICCs are ≥ 0.92 , while interrater ICCs range from 0.70 to 0.85 (Franettovich et al., 2007; Williams and McClay, 2000). Reliability and validity were higher for AHI than six other measurements, including navicular and dorsum height, foot length, and bony arch index (Williams and McClay, 2000). Therefore, AHI is one of our dependent variables.

Cowan et al. (1993) described bony arch index as the ratio of navicular (tuberosity) height to truncated foot length. Measurements have been taken in 50%, 90%, and 100% body weight (Cowan et al., 1993; McPoil and Cornwall, 2006). Nearly identical to bony arch index, Lees et al. (2005) defined arch index as the height of the navicular divided by foot length, extending from the heel to the distal end of the longest metatarsal (usually the first).

The longitudinal arch angle (LAA), also called supranavicular angle (Cashmere et al., 1999), was first proposed by Dahle et al. (1991). The LAA is the obtuse angle subtended by a line from the first metatarsal head to navicular tuberosity to medial malleolus. Intrarater ICCs are greater than 0.80 (Jonson and Gross, 1997; McPoil and Cornwall, 2005). Interrater ICCs, however, are lower (0.67 to 0.81), likely due to differences in identifying the three bony landmarks (Franettovich et al., 2007; Jonson and Gross, 1997; McPoil and Cornwall, 2005).

LAA at midstance of walking was $136.5^{\circ} \pm 11.0^{\circ}$, which is approximately a 2% decrease from standing LAA (McPoil and Cornwall, 2005). Cashmere et al. (1999) did not report absolute angles but did note a decrease to about 92% of seated LAA at about 85% of stance. McPoil and Cornwall (2007) noted greater decrease in LAA during running (10°)

than walking (3°) compared to standing, again corroborating that MLA collapse increases as loading increases.

Limitations of using LAA include some change in LAA may be due solely to internal tibial rotation that occurs with gait, and a large amount of skin movement over the navicular and medial malleolus, two of the landmarks used for LAA (Maslen and Ackland, 1994; Tranberg and Karlsson, 1998). Therefore, LAA will not be one of our dependent variables.

Another angular measurement of the MLA is the inferior angle from the first metatarsal head to navicular tuberosity to medial calcaneus. Individuals with medial tibial stress syndrome had a smaller MLA angle during standing and greater change in angle (1.7°) during walking compared to a control group, although 1.7° may not be clinically significant (Bandholm et al., 2008). The relationship between increased MLA deformation and medial tibial stress syndrome may be due to greater invertor or plantar flexor activity required to support the collapsing arch, which can lead to greater tibial-fascia traction that develops into medial tibial stress syndrome (Bouche and Johnson, 2007).

Similar to the MLA angle, Caravaggi et al. (2010) measured angular change in the MLA and noted deformation increased in the first half of stance as walking speed increased. However, in the second half, the arch was actually higher as speed increased.

2.4.1.3 Plantar Pressures. Typical progression of center of pressure during gait is slightly lateral on the heel, along the midline of the foot up to the metatarsals, and ends under the first or second toe (Song et al., 1996). As walking speed increased, peak pressures increased under the forefoot and rearfoot but decreased under the midfoot, and center of pressure shifted more medially (Pataky et al., 2008). Compared to walking, contact area, peak forces, and peak pressures are greater in running (Chuckpaiwong et al., 2008).

Song et al. (1996) noted no difference in peak pressures between low arch and neutral feet during gait. This was also supported by Williams et al. (2001) when evaluating running. Contrarily, other researchers have found greater pressures under the rearfoot in high arch individuals and greater medial midfoot force and pressure and a smaller center of pressure excursion index in low arch feet, indicating greater loading of the medial column of the foot than those with neutral arch morphology (Chuckpaiwong et al., 2008; Song et al., 1996; Xiong et al., 2010).

2.4.2 Foot Rigidity and Static Predictability. There is no consensus whether static foot type can predict the amount of dynamic MLA deformation. Typically, a higher arch is considered to be more rigid and a flatter arch more pliable (Frey, 1997). Even though higher arches were stiffer, static arch height only explained 9% of the variance in sit-to-stand arch stiffness (Zifchock et al., 2006), and other studies reported very weak or no relationship between static and MLA deformation during walking or running (Bandholm et al., 2008; Cashmere et al., 1999; Kaufman et al., 1999; Nachbauer and Nigg, 1992; Wearing et al., 1998).

Contrarily, several studies have shown strong correlations between static and dynamic foot motion. For example, standing dorsal arch height predicted 66% and 83% of the variance of dorsal arch height at midstance of walking and running, respectively (Franettovich et al., 2007). The same researchers compared standing AHI, and it too was highly correlated, predicting 72% and 76% of the variance in AHI at midstance of walking and running, respectively (Franettovich et al., 2007). High predictive values may be because Franettovich et al. (2007) had participants' feet one in front of the other as if taking a step. Standing LAA predicted about 85% of the variance of LAA at midstance of walking and

running (McPoil and Cornwall, 2005; McPoil and Cornwall, 2007). Internally rotating participants' leg and pronating their foot while standing could explain more of the variance (91%) of LAA during walking (McPoil and Cornwall, 2005). The aforementioned studies that reported high correlations all used 50% of stance for the dynamic comparison, but arch height is lowest at 70 to 85% of stance after heel rise (Caravaggi et al., 2010; Cashmere et al., 1999; Hunt et al., 2001; Wearing et al., 1998; Wearing et al., 1999), which may account for the high predictive values.

Arguably, arch stiffness measurements are better than other measurements because they account for loading changes. Before presenting data from other researchers, it is necessary to discuss the physics of stiffness and appropriate terminology. Only if displacements illicit a change in elastic energy should stiffness be used (Latash and Zatsiorsky, 1993). We are justified using stiffness as elastic energy storage is believed to occur in different tendons of the foot and ankle (Ker et al., 1987). Additionally, medial longitudinal arch stiffness is a combination of passive (tendons, fascia, ligaments) and active (muscles) components. Measuring muscle stiffness is difficult as it is time- and velocity-dependent, and the different components of muscle have different mechanical properties (Latash and Zatsiorsky, 1993). Because of these issues and because the current study quantifies dynamic arch stiffness, arch stiffness is technically quasi-stiffness.

Zifchock et al. (2006) defined arch stiffness as the change in AHI due to the increase in load from sitting to standing:

$$\frac{0.4 * BW}{AHI_{seat} - AHI_{stand}}$$

The authors assumed the MLA supported 10% body weight when sitting and 50% when standing—thus a 40% body weight increase. This assumption is obviously one weakness of the measurement as AHI may decrease as load increases. Nonetheless, arch stiffness was not different between dominant and non-dominant feet or between ages (18 to 65 year olds). However, women had more pliable arches than men, possibly because women in general have greater joint laxity (Remvig et al., 2007).

Additional arch stiffness measurements include relative arch deformity and arch rigidity index. Relative arch deformity, modified from its original definition, was defined as the percent change in dorsal arch height from 10% to 90% body weight (Williams and McClay, 2000). The equation is:

$$\frac{AHU - AH}{AHU} * \frac{10^4}{BW}$$

where BW is body weight; AHU is arch height at 10% BW; and AH is arch height at 90% BW. Arch rigidity index is the ratio of AHI during standing to sitting (Richards et al., 2003). Values closer to 1 represent a stiffer arch.

In vivo plantar fascia stiffness was calculated as the initial slope of a tension-elongation curve during walking. Mean stiffness was 170±45 N/mm for two female subjects during slow walking (Gefen, 2003).

Gender may partially explain arch rigidity, as hypermobility is generally more common in females than males (Remvig et al., 2007). Hypermobility was correlated to lower MLA height and increased plantar pressures under the medial midfoot during walking (Barber Foss et al., 2009; Kamanli et al., 2004; Kanatli et al., 2006). Women, therefore, may be at increased risk for MLA collapse-related injuries, evidenced by women with multiple

stress fractures reporting more fractures in the foot compared to men (Korpelainen et al., 2001). As such, the current study treated men and women as separate groups.

2.4.3 Foot Type and Injuries. Both low arch (pes planus) and high arch (pes cavus) feet have been associated with increased risk for athletic-related injury (Burns et al., 2005a; Cain et al., 2007; Kaufman et al., 1999; Korpelainen et al., 2001; Williams et al., 2001). For example, both low and high arch feet are associated with increased risk for all types of stress fractures, metatarsal stress fractures, and plantar fasciitis (Kamanli et al., 2004; Kanatli et al., 2006; Korpelainen et al., 2001; Taunton et al., 2002b; Williams et al., 2001).

Compared to high arch feet, flat feet had greater subtalar range of motion (Close et al., 1967), possibly leading to injuries associated with excessive pronation listed earlier. High arch feet, however, had greater internal tibial rotation than lower arches (Pohl et al., 2010), which is contradictory if low arch feet have greater subtalar motion and pronation is coupled to internal tibial rotation (Pohl and Buckley, 2008).

As mentioned earlier, high arch feet may be more rigid than low arch feet. This was supported by increased loading rate in high arch ($AHI \geq 0.356$) compared to low arch runners and shock-related bony injuries occurring more in high arch runners due to greater energy absorption in the foot and less force being propagated proximally (Williams et al., 2001; Williams et al., 2004). These bony injuries, however, may also be explained by increased overall lower extremity joint stiffness (Williams et al., 2004).

However, there was no absolute trend for arch type being related to tibial stress fractures, iliotibial band syndrome, patellofemoral syndrome, ankle or knee injuries, loading rate, or impact absorption during running (Barnes et al., 2008; Kaufman et al., 1999; Lees et al., 2005; Nachbauer and Nigg, 1992; Nakhaee et al., 2008). The discrepancy in loading rate

may be explained by heel versus forefoot strike (Lees et al., 2004; Nachbauer and Nigg, 1992; Williams et al., 2004), and the commonality of metatarsal stress fractures in both foot types may be explained by which metatarsals are affected. High arch feet were more likely to endure fifth metatarsal stress fractures while low arch feet endured more second or third metatarsal stress fractures (Williams et al., 2001). Additionally, the contradictions may be explained by a more flexible foot in gait, regardless of static height, resulting in increased metatarsal stress fractures (Kaufman et al., 1999). Overall, the ambiguous relationship between foot type and overuse injuries is likely because most foot type assessments were done statically and not dynamically and multiple types of measurements were used. Regardless of foot type, a prospective study reported that injured runners had greater tibial accelerations, vertical impact peak, and average vertical loading rate compared to those who never were injured (Davis et al., 2010). Therefore, identifying if the amount of MLA deformation is associated with these variables may help predict which runners will get injured.

Some associations between arch type and injuries should be interpreted cautiously as some researchers did not use normative values to distinguish flat, neutral, or high arches (Kaufman et al., 1999; Nachbauer and Nigg, 1992; Xiong et al., 2010). Kaufman et al. (1999) divided 449 participants into tertiles and Xiong et al. (2010) and Nachbauer and Nigg (1999) divided participants into the top and bottom quartiles, which would overestimate the number of participants in the high and low arch groups since 15 to 20% of the population has high arch feet and up to 20% has low arch feet (Subotnick, 1985; Walker and Fan, 1998).

2.5 External Motion Control

Some investigators assert that running shoes alter how people run, and whether the changes are beneficial or harmful is debatable. A stiffer medial midsole in running shoes functions to decrease pronation, which ultimately is supposed to prevent injuries. These types of shoes are sometimes called motion control shoes. After a 1.5 km run, rearfoot angle and peak forces under the first metatarsal head and medial midfoot were greater in cushion shoes compared to motion control shoes (Cheung and Ng, 2008). Motion control shoes showed no difference in plantar loading, implying less MLA collapse/medial column loading. Since there is a possibility shoes may influence the amount of MLA deformation during running, running shoe type was recorded in the current study but participants ran in their personal shoes.

Orthotics and athletic taping aim to correct abnormal or painful mechanics, but orthotic effectiveness is contentious during walking as Bellchamber and van den Bogert (2000) found proximal-to-distal power flow between the shank and foot. However, during running, power flow may be reversed and orthotics may serve their purpose. One study reported only an extreme posterior orthotic significantly reduced eversion during running compared to barefoot running (Stacoff et al., 2000). On the other hand, about 75% of distance runners reported orthotics being beneficial (Gross et al., 1991). Perhaps more successful, anti-pronation tape increased dorsal arch height 8 mm (12.9%) in low arch feet immediately after taping, accompanied by a decrease in tibialis posterior EMG amplitude (one of the major arch-supporting muscles) (Franettovich et al., 2008). Those changes were not permanent, though, because arch height decreased 3 mm from the original 8 mm after 10 minutes of barefoot treadmill walking.

2.6 Changes after Long Runs/Fatigue

Since it is suggested that injury potential is greater toward the end of exercise (Whiting and Zernicke, 1998, p. 119), it is crucial to identify changes that occur over the progression of a long run. Since the foot interacts with the ground and may influence tibial motion during running (Bellchamber and van den Bogert, 2000), it is especially important to investigate how foot function may change. Non-fatigued muscles may absorb shock during running and fatigued muscles may be less effective (Friesenbichler et al., 2010; Yoshikawa et al., 1994). Also, a fatigued muscle may not protect bones from bending moments, which increases risk for injury (Sharkey et al., 1995).

Several researchers have identified different plantar pressure patterns after fatiguing exercise bouts (Nagel et al., 2008; Stolwijk et al., 2010; Weist et al., 2004; Wu et al., 2007). Barefoot walking after a marathon showed increased forefoot pressures and decreased toe pressures (Nagel et al., 2008). Similar results were seen after walking 161 km or more over four days (Stolwijk et al., 2010). Arch index (contact area of midfoot divided by whole foot area minus toes) did not change post-marathon (Nagel et al., 2008). Weist et al. (2004) and Wu et al., (2007) showed similar increases under the metatarsal heads after running 13.6 and 20 minutes, respectively, in addition to increased pressure under the medial midfoot, which increased primarily because of force not contact area (Weist et al., 2004; Wu et al., 2007). Nagel et al. (2008) argued that a shift in pressure to the metatarsal heads away from the toes may be due to fatiguing the toe flexors and increasing dorsiflexion. This shift to greater forefoot loading may increase risk for metatarsal stress fractures, agreeing with second metatarsal strain and strain rate increasing after prolonged barefoot walking (Arndt et al., 2002).

However, during a typical 90 minute running session, no changes in peak pressure, impulse, time to peak, and contact time were observed among six plantar regions (Deleu et al., 2010). Similarly, Schlee et al. (2009) found no changes in plantar pressures after a 45 minute run, even though participants ran at a pace near maximum lactate steady state. While exertion level was not reported by Deleu et al., (2010) besides that it was at self-selected speed, fatigue may not have ensued, which may explain why there were no significant changes.

Several investigators have found tibial impacts increased in the latter part of an exhaustive run (Derrick et al., 2002; Mizrahi et al., 1997; Mizrahi et al., 2000a; Mizrahi et al., 2000b). This may be indicative of changes in foot mechanics due to the coupling of the shank and foot and the arch's function as a shock absorber. Whether impacts change may depend on fatigue level, because tibial accelerations increased in people who were fatigued and were unchanged in others who were not fatigued after a 30 minute run (Mizrahi et al., 1997). Selectively fatiguing the dorsiflexors and plantarflexors (not during running) decreased tibial accelerations (Flynn et al., 2004). Flynn et al. (2004) argued that whole body fatigue may not result in local muscle fatigue and changes in tibial acceleration may be more due to kinematic changes, such as a more flexed knee at heel-strike (4.4°) and increase knee flexion velocity (Derrick et al., 2002).

Loading rates have been reported to remain unchanged after a prolonged run above lactate threshold (Schlee et al., 2009) or decrease after a graded exercise test (Gerlach et al., 2005). Perhaps the MLA became less stiff after the run which decreased loading rate. This supports previous findings that a runner can sense impact forces and adapts his or her running style to abate high frequency forces (Milani et al., 1997). Considering that loading

rate has been proposed as a likely injury mechanism (Davis et al., 2010), this would imply that injury likelihood decreases or is unaltered towards an end of a run, which is contrary to general belief.

2.7 Summary

Collectively, mechanical changes at the foot likely affect other lower limb kinematics and kinetics through the ankle joint complex. After a prolonged run, the MLA may deform more due to its viscoelastic properties and fatiguing the arch-supporting muscles. Greater deformation may cause greater tension and strain of the plantar fascia, possibly leading to plantar fasciitis, or the decrease muscle tension from fatigue may increase bone strain and risk for metatarsal stress fractures. Using 3-D motion capture, however, it has yet to be investigated if medial longitudinal arch deformation changes after a long run. Furthermore, because injury is unlikely from jogging a few meters, it is likely overuse injuries develop after running several miles or reaching a more fatigued state. Since the majority of training is at a comfortable intensity and not an exhausting race-pace, it is probable injuries begin to develop at lower intensities. Therefore, our study looked at changes in medial longitudinal arch mechanics before and after a 45 minute run at a comfortable pace. We also compared walking and running arch deformation as this is rarely done in previous studies.

REFERENCES

- Arndt, A., Ekenman, I., Westblad, P., and Lundberg, A. (2002). Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *Journal of Biomechanics*, 35(5), 621-8.
- Arndt, A., Wolf, P., Liu, A., Nester, C., Stacoff, A., Jones, R., Lundgren, P., and Lundberg, A. (2007). Intrinsic foot kinematics measured in vivo during the stance phase of slow running. *Journal of Biomechanics*, 40(12), 2672-2678.
- Bandholm, T., Boysen, L., Haugaard, S., Kreutzfeldt Zebis, M., and Bencke, J. (2008). Foot medial longitudinal-arch deformation during quiet standing and gait in subjects with medial tibial stress syndrome. *The Journal of Foot and Ankle Surgery*, 47(2), 89-95.
- Barber Foss, K.D., Ford, K.R., Myer, G.D., and Hewett, T.E. (2009). Generalized joint laxity associated with increased medial foot loading in female athletes. *Journal of Athletic Training*, 44(4), 356-362.
- Barnes, A., Wheat, J., and Milner, C. (2008). Association between foot type and tibial stress injuries: a systematic review. *British Journal of Sports Medicine*, 42(2), 93-8.
- Basmajian, J. and Stecko, G. (1963). The role of muscles in support of the arch of the foot. *Journal of Bone and Joint Surgery*, 45, 1184-90.
- Beckett, M.E., Massie, D.L., and Bowes, K.D. (1992). Incidence of hyperpronation in the ACL injured knee. *Journal of Athletic Training*, 27(1), 58-60.
- Bellchamber, T.L. and van den Bogert, A.J. (2000). Contributions of proximal and distal moments to axial tibial rotation during walking and running. *Journal of Biomechanics*, 33, 1397-1403.
- Bennett, J.E., Reinking, M.F., Pluemer, B., Pentel, A., Seaton, M., and Killian, C. (2001). Factors contributing to the development of medial tibial stress syndrome in high school runners. *Journal of Orthopaedica and Sports Physical Therapy*, 31(9), 504-10.
- Billis, E., Katsakiori, E., Kapodistrias, C., and Kapreli, E. (2007). Assessment of foot posture: Correlation between different clinical techniques. *The Foot*, 17, 65-72.
- Bouché, R.T. and Johnson, C.H. (2007). Medial tibial stress syndrome (tibial fasciitis): A proposed pathomechanical model involving fascial traction. *Journal of the American Podiatric Medical Association*, 97(1), 31-36.
- Brody, D.M. (1982). Techniques in the evaluation and treatment of the injured runner. *The Orthopedic Clinics of North America*, 13, 541-58.

- Burns, J., Keenan, A-M., and Redmond, A. (2005a). Foot Type and Overuse Injury in Triathletes. *Journal of the American Podiatric Medical Association*, 95(3), 235-241.
- Cain, L.E., Nicholson, L.L., Adams, R.D., and Burns, J. (2007). Foot morphology and foot/ankle injury in indoor football. *Journal of Science and Medicine in Sport*, 10(5), 311-319.
- Caravaggi, P., Pataky, T., Gunther, M., Savage, R., and Crompton, R. (2010). Dynamics of longitudinal arch support in relation to walking speed: Contribution of the plantar aponeurosis. *Journal of Anatomy*, 217, 254-61.
- Cashmere, T., Smith, R., and Hunt, A. (1999). Medial longitudinal arch of the foot: stationary versus walking measures. *Foot and Ankle International*, 20(2), 112-8.
- Cheung, J.T-M., Zhang, M., and An, K-N. (2006). Effect of Achilles tendon loading on plantar fascia tension in the standing foot. *Clinical Biomechanics*, 21, 194–203.
- Cheung, R.T.H. and Ng, G.Y.F. (2008). Influence of different footwear on force of landing during running. *Physical Therapy*, 88(5), 620-628.
- Chuckpaiwong, B., Nunley, J.A., Mall, N.A., and 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.
- Clement, D.B., Taunton, J.E., Smart, G.W. (1984). Achilles tendinitis and peritendinitis: Etiology and treatment. *American Journal of Sports Medicine*, 12(3), 179-184.
- Close, J.R., Inman, V.T., Poor, P.M., and Todd, F.N. (1967). The function of the subtalar joint. *Clinical Orthopaedics*, 50, 159-79.
- Cornwall, M. and McPoil, T. (1999). Relative movement of the navicular bone during normal walking. *Foot and Ankle International*, 20, 507–512.
- Cowan, D., Jones, B., and Robinson, J. (1993). Foot morphologic characteristics and risk of exercise-related injury. *Archives of Family Medicine*, 2, 773-7.
- Dahle, L., Mueller, M., Delitto, A., and Diamond, J. (1991). Visual assessment of foot type and relationship of foot type to low extremity injury. *Journal of Orthopaedic Sports and Physical Therapy*, 14, 70-74.
- Davis, IS., Bowser, B., and Mullineaux, D. (2010). Do impacts cause running injuries? A prospective investigation. *Proceedings of the American Society of Biomechanics 34th Annual Meeting*.

- Deleu, P.A., Deschamps, K., Leemrijse, T., Matricali, G. (2010). Impact of 90 minutes running exercise on plantar loading of the forefoot: A prospective study on symptom-free athletes. *Journal of Bone and Joint Surgery (British Volume)*, 92-B(Supp 4), 585.
- Derrick, T.R., Dereu, D., and McLean, S.P. (2002). Impacts and kinematic adjustments during an exhaustive run. *Medicine and Science in Sports and Exercise*, 34(6), 998-1002.
- Donahue, S.W. and Sharkey, N.A. (1999). Strains in the metatarsals during the stance phase of gait: Implications for stress fractures. *The Journal of Bone and Joint Surgery*, 81, 1236-44.
- Elftman, H. (1960). The transverse tarsal joint and its control. *Clinical Orthopaedics*, 16, 41-46.
- Erdemir, A., Hamel, A.J., Fauth, A.R., Piazza, S.J., and Sharkey, N.A. (2004). Dynamic loading of the plantar aponeurosis in walking. *The Journal of Bone and Joint Surgery (American)*, 86, 546-552.
- Ferber, R., Hreljac, A., and Kendall, K.D. (2009). Suspected mechanisms in the cause of overuse running injuries: A clinical review. *Athletic Training*, 1(3), 242-6.
- Fiolkowski, P., Brunt, D., Bishop, M., Woo, R., Horodyski, M.B. (2003). Intrinsic pedal musculature support of the medial longitudinal arch: an electromyography study. *The Journal of Foot and Ankle Surgery*, 42(6), 327-33.
- Flynn, J.M., Holmes, J.D., and Andrews, D.M. (2004). The effect of localized leg muscle fatigue on tibial impact acceleration. *Clinical Biomechanics*, 19(7), 726-732.
- Franettovich, M., Chapman, A., and Vicenzino, B. (2008). Tape that increases medial longitudinal arch height also reduces leg muscle activity: A preliminary study. *Medicine and Science in Sports and Exercise*, 40, 593-600.
- Franettovich, M., McPoil, T., Russell, T., Skardoon, G., and Vicenzino, B. (2007). The ability to predict dynamic foot posture from static measurements. *Journal of the American Podiatric Medical Association*, 97(2), 115-120.
- Frey, C. (1997). Footwear and stress fractures. *Clinics in Sports Medicine*, 16(2), 249-257.
- Friesenbichler, B. Stirling, L.M., Federolf, P., and Nigg, B.M. (2010). Tissue vibration in prolonged running. *Journal of Biomechanics*, DOI: 10.1016/j.jbiomech.2010.08.034.
- Gefen, A. (2003). The in vivo elastic properties of the plantar fascia during the contact phase of walking. *Foot and Ankle International*, 24(3), 238-44.
- Geideman, W.M. and Johnson, J.E. (2000). Posterior Tibial Tendon Dysfunction. *Journal of Orthopaedic and Sports Physical Therapy*, 30 (2), 68-77.

Gerlach, K.E., White, S.C., Burton, H.W., Dorn, J.M., Leddy, J.J., and Horvath, P.J. (2005). Kinetic changes with fatigue and relationship to injury in female runners. *Medicine and Science in Sports and Exercise*, 37(4), 657-663.

Giddings, V.L., Beaupre, G.S., Whalen, R.T., and Carter, D.R. (2000). Calcaneal loading during walking and running. *Medicine and Science in Sports and Exercise*, 32(3), 627-634.

Gross, M.L., Davlin, L.B., Evanski, P.M. (1991). Effectiveness of orthotic shoe inserts in the long-distance runner. *American Journal of Sports Medicine*, 19(4), 409-412.

Hamill, J. and Knutzen, K.M. 2003. *Biomechanical Basis of Human Movement* (2nd ed.). Lippincott Williams & Wilkins, pp. 207-214, 414, 432.

Headlee, D., Leonard, J., Hart, J., Ingersoll, C., and Hertel, J. (2008). Fatigue of the plantar intrinsic foot muscles increases navicular drop. *Journal of Electromyography and Kinesiology*, 18, 420-425.

Hicks, J.H. (1954). The mechanics of the foot. II. The plantar aponeurosis and the arch. *Journal of Anatomy*, 88, 25-30.

Hintermann, B. and Nigg, B.M. (1998). Pronation in runners: Implications for injuries. *Sports Medicine*, 26(3), 169-176.

Huang, C.K., Kitaoka, H.B., An, K.N., and Chao, E.Y. (1993). Biomechanical evaluation of longitudinal arch stability. *Foot and Ankle*, 14(6), 353-357.

Hunt, A.E., Smith, R.M., Torode, M., and Keenan, A.M. (2001). Inter-segment foot motion and ground reaction forces over the stance phase of walking. *Clinical Biomechanics (Bristol, Avon)*, 16, 592-600.

Jam B. (2006). Evaluation and retraining of the intrinsic foot muscles for pain syndromes related to abnormal control of pronation. Advanced Physical Therapy Education Institute. <http://www.aptei.com/articles/pdf/IntrinsicMuscles.pdf>. Accessed November, 11, 2010.

Jonson, S.R. and Gross, M.T. (1997). Intraexaminer reliability, interexaminer reliability, and mean values for nine lower extremity skeletal measures in healthy naval midshipmen. *Journal of Orthopaedic and Sports Physical Therapy*, 25, 253-63.

Kamanli, A., Sahin, S., Ozgocmen, S., Kavuncu, V., and Ardicoglu, O. (2004). Relationship between foot angles and hypermobility scores and assessment of foot types in hypermobile individuals. *Foot and Ankle International*, 25(2), 101-6.

Kanatli, U., Gozil, R., Besli, K., Yetkin, H., and Bolukbasi, S. (2006). The relationship between the hindfoot angle and the medial longitudinal arch of the foot. *Foot and Ankle International*, 27(8), 623-27.

- Kastelic, J. and Baer, E. (1980). Deformation in tendon collagen. *Symposia of the Society for Experimental Biology*, 34, 397-435.
- Kaufman, K.R., Brodine, S.K., Shaffer, R.A., Johnson, C.W., and Cullison, T.R.. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. *American Journal of Sports Medicine*, 27(5), 585-593.
- Kayano, J. (1986). Dynamic function of the medial foot arch. *Nippon Seikeigeka Gakki Zasshi*, 60, 1147-1156.
- Kaye, R.A. and Jahss, M.H. (1991). Tibialis posterior: a review of anatomy and biomechanics in relation to support of the medial longitudinal arch. *Foot and Ankle*, 11, 244-247.
- Ker, R., Bennett, M., Bibby, S.R., Kester, R.C., and Alexander, R. (1987). The spring in the arch of the human foot. *Nature*, 325, 147-49.
- Kirby, K.A. (2000). Biomechanics of the normal and abnormal foot. *Journal of the American Podiatric Medical Association*, 90(1), 30-34.
- Korpelainen, R., Orava, S., Karpakka, J., Siira, P., and Hulkko, A. (2001). Risk factors for recurrent stress fractures in athletes. *American Journal of Sports Medicine*, 29, 304-10.
- Latash, M.L. and Zatsiorsky, V.M. (1993). Joint stiffness: Myth or reality? *Human Movement Science*, 12, 653-92.
- Lees, A., Lake, M., and Klenerman, L. (2005). Shock absorption during forefoot running and its relationship to medial longitudinal arch height. *Foot and Ankle International*, 26, 1081-8.
- Loudon, J.K., Jenkins, W., and Loudon, K.L. (1996). The relationship between static posture and ACL injury in female athletes. *Journal of Orthopaedic and Sports Physical Therapy*, 24(2), 91-7.
- Maganaris, C.N., Baltzopoulos, V., and Sargeant, A.J. (2002). Repeated contractions alter the geometry of human skeletal muscle. *Journal of Applied Physiology*, 93,2089-2094.
- Mann, R. and Inman, V.T. (1964). Phasic activity of intrinsic muscles of the foot. *Journal of Bone and Joint Surgery (American)*, 46, 469-481.
- Markolf, K.L., Mensch, J.S., and Amstutz, H.C. (1976). Stiffness and laxity of the knee--the contributions of the supporting structures. A quantitative in vitro study. *Journal of Bone and Joint Surgery (American)*, 5, 583-594.
- Maslen, B. and Ackland, T. (1994). Radiographic study of the skin displacement errors in the foot and ankle during standing. *Clinical Biomechanics*, 9, 291-6.

- Mathieson, I., Upton, D., and Prior, T.D. (2004). Examining the validity of selected measures of foot type: A preliminary study. *Journal of the American Podiatric Medical Association*, 94(3), 275-281.
- McPoil, T. and Cornwall, M. (2005). Use of the longitudinal arch angle to predict dynamic foot posture in walking. *Journal of the American Podiatric Medicine Association*, 95(2), 114-120.
- McPoil, T.G. and Cornwall, M.W. (1994). Relationship between neutral subtalar joint position and pattern of rearfoot motion during walking. *Foot and Ankle International*, 15(3), 141-5.
- McPoil, T.G. and Cornwall, M.W. (2006). Use of plantar contact area to predict medial longitudinal arch height during walking. *Journal of the American Podiatric Medical Association*, 96(6), 489-494.
- McPoil, T.G. and Cornwall, M.W. (2007). Prediction of dynamic foot posture during running using the longitudinal arch angle. *Journal of the American Podiatric Medicine Association*, 97(2), 102-107.
- McPoil, T.G., Cornwall, M.W., Medoff, L., Vicenzino, B., Forsberg, K., and Hilz, D. (2008a). Arch height change during sit-to-stand: an alternative for the navicular drop test. *Journal of Foot and Ankle Research*, 1:3.
- McPoil, T.G., Cornwall, M.W., Vicenzino, B., Teyhen, D.S., Molloy, J., Christie, D., and Collins, N. (2008b). Effect of using truncated versus total foot length to calculate the arch height ratio. *The Foot*, 18(4), 220-7.
- McPoil, T.G., Vicenzino, B., Cornwall, M.W., Collins, N., and Warren, M. (2009). Reliability and normative values for the foot mobility magnitude: a composite measure of vertical and medial-lateral mobility of the midfoot. *Journal of Foot and Ankle Research*, 2:6.
- Menz, H.B. (1998). Alternative techniques for the clinical assessment of foot pronation. *Journal of the American Podiatric Medicine Association*, 88, 119–129.
- Michelson, J.D., Durant, D.M., and McFarland, E. (2003). Injury risk associated with pes planus in athletes. *Foot and Ankle International*, 23(7), 629–933.
- Milani, T.L., Hennig, E.M., and Lafortune, M.A. (1997). Perceptual and biomechanical variables for running in identical shoe constructions with varying midsole hardness. *Clinical Biomechanics*, 12(5), 294-300.
- Mizrahi, J., Verbitsky, O., and Isakov, E. (2000a). Fatigue-related loading imbalance on the shank in running: A possible factor in stress fractures. *Annals of Biomedical Engineering*, 28, 463-469.

Mizrahi, J., Verbitsky, O., Isakov, E., and Daily, D. (2000b). Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Human Movement Science*, 19, 139-151.

Mizrahi, J., Voloshin, A., Russek, D., Verbitsky, O., and Isakov, E. (1997). The influence of fatigue on EMG and impact acceleration in running. *Basic and Applied Myology*, 7(2), 111-118.

Murley, G., Menz, H., and Landorf, K. (2009b). Foot posture influences the electromyographic activity of selected lower limb muscles during gait. *Journal of Foot and Ankle Research*, 2, 35-43.

Murley, G.S., Buldt, A.K., Trump, P.J., and Wickham, J.B. (2009a). Tibialis posterior EMG activity during barefoot walking in people with neutral foot posture. *Journal of Electromyography and Kinesiology*, 19(2), p.69-77.

Nachbauer, W. and Nigg, B.M. (1992). Effects of arch height of the foot on ground reaction forces in running. *Medicine in Science and Sports Medicine*, 24(11), 1264-9.

Nagel, A., Ferfnholz, F., Kibele, C., and Rosenbaum, D. (2008). 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.

Nakhaee, Z., Rahimi, A., Abaee, M., Rezasoltani, A. and Kalantari, K. K. (2008). The relationship between the height of the medial longitudinal arch (MLA) and the ankle and knee injuries in professional runners. *Foot (Edinburgh, Scotland)*, 18(2), 84-90.

Nester, C.J., Liu, A.M., Ward, E., Howard, D., Cocheba, J., and Derrick, R. (2010). Error in the description of foot kinematics due to violation of rigid body assumptions. *Journal of Biomechanics*, 43(4), 666-672.

Nielsen, R., Rathleff, M., Simonsen, O., and Langberg, H. (2009). Determination of normal values for navicular drop during walking: A new model correcting for foot length and gender. *Journal of Foot and Ankle Research*, 2, 12-18.

Nigg, B.M. and Herzog, W. (Eds.). (1994). *Biomechanics of the Musculoskeletal System*. West Sussex, England: John Wiley and Sons, p. 117.

Nigg, B.M., Cole, G.K., and Nachbauer, W. (1993). Effects of arch height of the foot on angular motion of the lower extremities in running. *Journal of Biomechanics*, 26(8), 909-916.

Ogon, M., Aleksiev, A.R., Pope., M.H., Wimmer, C., and Saltzman, C.L. (1999). Does arch height affect impact loading at the lower back level in running? *Foot and Ankle International*, 20, 263-66.

Pataky, T.C., Caravaggi, P., Savage, R., Parker, D., Goulermas, J.Y., Sellers, W.I., and Crompton, R.H. (2008). New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM). *Journal of Biomechanics*, 41(9), 1987-94.

Perry, J. 1992. *Gait Analysis -Normal, and Pathological Function*. Thorofare, NJ: Slack, Inc., pp. 51–87.

Perry, S.D. and Lafortune, M.A. (1995). Influences of inversion/eversion of the foot upon impact loading during locomotion. *Clinical Biomechanics*, 10(5), 253-257.

Plisky, M.S., Rauh, M.J., Heiderscheit, B., Underwood, F.B., and Tank, R.T. (2007). Medial tibial stress syndrome in high school cross-country runners: Incidence and risk factors. *Journal of Orthopaedic and Sports Physical Therapy*, 37(2), 40-47.

Pohl, M.B. and Buckley J.G. (2008). Changes in foot and shank coupling due to alterations in foot strike pattern during running. *Clinical Biomechanics*, 23, 334-41.

Pohl, M.B., Hamill, J., and Davis, I.S. (2009). Biomechanical and Anatomic Factors Associated with a History of Plantar Fasciitis in Female Runners. *Clinical Journal of Sport Medicine*, 19(5), 372-6.

Pohl, M.B., Rabbito, M., and Ferber, R. (2010). The relationship between static arch rigidity and foot kinematics during gait. *Proceedings of the 2nd Congress of the International Foot and Ankle Biomechanics Community*.

Razeghi, M. and Batt, M.E. (2002). Foot type classification: a critical review of current methods. *Gait and Posture*, 15(3), 282-291.

Reber, L., Perry, J., and Pink, M. (1993). Muscular control of the ankle in running. *American Journal of Sports Medicine*, 21(6), 805-10.

Remvig, L., Jensen, D., and Ward, R. (2007). Epidemiology of general joint hypermobility and basis for the proposed criteria for benign joint hypermobility syndrome: Review of the literature. *The Journal of Rheumatology*, 34(4), 804-9.

Richards, C.J., Card, K., Song, J., Hillstrom, H., Butler, R., and Davis, I.M. (2003). A novel arch height index measurement system (AHIMS): Intra- and inter-rater reliability. *Proceedings of the American Society of Biomechanics 26th Annual Meeting*.

Riegger, C.L. (1988). Anatomy of the Ankle and Foot. *Physical Therapy*, 63(12), 1802-14.

Ringleb, S., Kavros, S., Kotajarvi, B., Hansen, D., Kitaoka, H., and Kaufman, K. (2007). Changes in gait associated with acute stage II posterior tibial tendon dysfunction. *Gait and Posture*, 25, 555-64.

Salathe, E.P. and Arangio, G.A. (2002). A biomechanical model of the foot: The role of muscles, tendons, and ligaments. *Journal of Biomedical Engineering*, 124, 281-87.

Saltzman, C., Nawoczenski, D., and Talbot, K. (1995). Measurement of the medial longitudinal arch. *Archives of Physical Medicine and Rehabilitation*, 76, 45-49.

Schlee, G., Milani, T., and Roemer, K. (2009). Plantar pressure distribution, rearfoot motion and ground reaction force after long distance running. *Footwear Science*, 1(3), 129-134.

Sell, K.E., Verity, T.M., Worrell, T.W., Pease, B.J., and Wigglesworth, J. (1994). Two measurement techniques for assessing subtalar joint position: a reliability study. *Journal of Orthopaedic and Sports Physical Therapy*, 19(3), 162-7.

Semple, R., Murley, G., Woodburn, J., and Turner, D. (2009). Tibialis posterior in health and disease: a review of structure and function with specific reference to electromyographic studies. *Journal of Foot and Ankle Research*, 2, 24.

Sharkey, N. A., Ferris, L., Smith, T. S., and Matthews, D. K. (1995). Strain and loading of the second metatarsal during heel-lift. *Journal of Bone and Joint Surgery (American)*, 77(7), 1050-7.

Sharkey, N.A., Donahue, S.W., and Ferris, L. (1999). Biomechanical consequences of plantar fascial release or rupture during gait. Part II: Alterations in forefoot loading. *Foot and Ankle International*, 20(2), 86-96.

Simkin, A., Leichter, I., Giladi, M., Stein, M., and Milgrom, C. (1989). Combined effect of foot arch structure and an orthotic device on stress fractures. *Foot and Ankle*, 10(1), 25-9.

Snook, A.G. (2001). The relationship between excessive pronation as measured by navicular drop and isokinetic strength of the ankle musculature. *Foot and Ankle International*, 22(3), 234-40.

Song, J., Hillstrom, H.J, Secord, D., and Levitt, J. (1996). Foot type biomechanics comparison of planus and rectus foot types. *Journal of the American Podiatric Medical Association*, 86(1), 16-23.

Stacoff, A., Nigg, B., Reinschmidt, C., van den Bogert, A.J., and Lundberg., A.(2000). Tiobiocalcaneal kinematics of barefoot versus shod running. *Journal of Biomechanics*, 33, 1387-95.

Stolwijk, N.M., Duysens, J., Louwerens, J.W.K., and Keijsers, N.L.W. (2010). Plantar pressure changes after long distance walking. *Medicine and Science in Sports and Exercise*, DOI: 10.1249/MSS.0b013e3181e305f4.

- Subotnick, S.I. (1985). The biomechanics of running: Implications for the prevention of foot injuries. *Sports Medicine*, 2, 144-153.
- Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., and Lloyd-Smith, R. (2002a). Plantar fasciitis: A retrospective analysis of 267 cases. *Physical Therapy in Sports*, 3, 57-65.
- Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R., and Zumbo, B.D. (2002b). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, 36, 95-101.
- Thordarson, D.B., Hedman, T., Lundquist D., and Reisch, R. (1998). Effect of calcaneal osteotomy and plantar fasciotomy on arch configuration in a flatfoot model. *Foot and Ankle International*, 19(6), 374-8.
- Tranberg, R. and Karlsson, D. (1998). The relative skin movement of the foot: A 2-D roentgen photogrammetry study. *Clinical Biomechanics*, 13, 71-6.
- Vinicombe, A., Raspovic, A., and Menz, H. (2001). Reliability of navicular displacement measurement as a clinical indicator of foot posture. *Journal of the American Podiatric Medicine Association*, 91, 262-8.
- Voigt, M., Bojsen-Moller, F., Simonsen, E.B., and Dyhre-Poulsen, P. (1995). The influence of tendon Young's modulus, dimensions and instantaneous moment arms on the efficiency of human movement. *Journal of Biomechanics*, 28, 281-291.
- Walker, M. and Fan, H.J., (1998). Relationship between foot pressure pattern and foot type, *Foot and Ankle International*, 19, 379-383.
- Ward, E.D., Smith, K.M., Cocheba, J.R., Patterson, P.E., and Phillips, R.D. (2003). In vivo forces in the plantar fascia during the stance phase of gait. Sequential release of the plantar fascia. *Journal of the American Podiatric Medical Association*, 93(6), 429-442.
- Wearing, S., Smeathers J., Yates, B., Sullivan, P., Urry, S., and Dubois, P. (2004). Sagittal movement of the medial longitudinal arch is unchanged in plantar fasciitis. *Medicine and Science in Sports and Exercise*, 36(10), 1761-7.
- Wearing, S.C., Urry, S., Perlman, P., Dubois, P., and Smeathers, J. (1999). Serial measurement of calcaneal pitch during midstance. *Journal of the American Podiatric Medical Association*, 89(4), 188-93.
- Wearing, S.C., Urry, S., Perlman, P., Smeathers, J., and Dubois, P. (1998). Sagittal plane motion of the human arch during gait: A videofluoroscopic analysis. *Foot and Ankle International*, 19(11), 738-42.

- Weist, R., Eils, E., and Rosenbaum, D. (2004). The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *American Journal of Sports Medicine*, 32(8), 1893-98.
- Whiting, W. and Zernicke, R. (2008). *Biomechanics of musculoskeletal injury* (2nd ed.). United States of America: Human Kinetics, pp. 90, 91, 115.
- Whiting, W.C. and Zernicke, R.F. (1998). *Biomechanics of Musculoskeletal Injury*. Champaign, IL: Human Kinetics, p.119.
- Williams, D., McClay, I., and Hamill, J. (2001). Arch structure and injury patterns in runners. *Clinical Biomechanics*, 16, 341-7.
- Williams, D.S. and McClay, I.S. (2000). Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. *Physical Therapy*, 80(9), 864-71.
- Williams, D.S., McClay Davis, I., Scholz, J.P., Hamill, J., and Buchanan, T.S. (2004). High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait and Posture*, 19(3), 263-269.
- Wolf, P., Stacoff, A., Liu, A., Nester, C., Arndt, A., Lundberg, A., and Stuessi, E. (2008). Functional units of the human foot. *Gait and Posture*, 28, 434-441.
- Wu, W.L., Chang, J.J., Wu, J.H., Guo, L.Y., and Lin, H.T. (2007). EMG and Plantar Pressure Patterns after Prolonged Running. *Biomedical Engineering: Applications, Basis and Communications*, 19(6), 383-388.
- Xiong, S., Goonetilleke, R.S., Witana, C.P., Weerasinghe, T.W., and Au, E.Y.L. (2010). Foot Arch Characterization. A Review, a New Metric, and a Comparison. *Journal of the American Podiatric Medical Association*, 100(1), 14-24.
- Yang, S.M., Kayano, J., Norimatsu, T. Fujita, M., Matsusaka, N., and Suzuki, R. (1985). Dynamic changes of the arches of the foot during walking, in: *Biomechanics IX-A*, Winter, D.A., Norman, R.W., Wells, R.P., Hayes, K.C., and Patla, A.E. (Eds.). Champaign, IL: Human Kinetics Publishers, pp. 417-422.
- Yoshikawa, T., Mori, S., Santiesteban, A.J., Sun, T.C., Hafstad, E., Chen, J., and Burr, D.B. (1994). The effects of muscle fatigue on bone strain. *Journal of Experimental Biology*, 188, 217-233.
- Zelik, K.E. and Kuo, A.D. (2010). Moving and shaking: Soft tissue work in human walking. *Proceedings of the American Society of Biomechanics 34th Annual Meeting*.

Zifchock, R.A., Davis, I., Hillstrom, H., and Song, J. (2006). The effect of gender, age, and lateral dominance on arch height and arch stiffness. *Foot and Ankle International*, 27(5), 367-72.

CHAPTER 3. MEDIAL LONGITUDINAL ARCH MECHANICS BEFORE AND AFTER A PROLONGED RUN

A paper to be submitted to *Clinical Biomechanics*

Elizabeth R. Hageman, Erin D. Ward, Timothy R. Derrick

ABSTRACT

Background. Collapse and reformation of the medial longitudinal arch during gait is controlled passively and actively. If either tissue group fatigues over the duration of a run, the change in arch mechanics may increase risk of running injuries. However, a 3-dimensional kinematic analysis of the medial longitudinal arch after a prolonged run has not been performed. Additionally, rarely has arch collapse been quantified for walking and running in the same study.

Methods. Thirty runners performed barefoot walking and running trials before and after a 45 minute run. Reflective markers were placed on the foot and lower limb. Navicular displacement, arch lengthening, and arch height index quantified arch motion. Arch rigidity index and dynamic arch stiffness, a new measurement, quantified arch stiffness.

Findings. There was a significant gender \times time interaction, with arch rigidity index decreasing after the run for men and increasing for women. There was no main effect for either time or gender for any other dependent variable. Walking and running were significantly different for all relevant variables. Arch collapse was significantly greater for running than walking.

Interpretation. The structures of the medial longitudinal arch of the foot may adapt to the cyclical loading of the run by recruiting other muscles, or the arch may be resilient to change after a non-exhausting run. Greater arch deformation during running was likely a

function of increased plantarflexion moment and ground reaction forces compared to walking.

1. INTRODUCTION

Faulty mechanics at the foot/ground interface may cause injuries at the foot or elsewhere up the kinetic chain because a coupling exists between rearfoot motion and tibial rotation (Pohl and Buckley, 2008), but the association between foot structure and injury risk is ambiguous. Understanding the foot as a dynamic structure with changing material properties and whether it functions differently after a long run may help identify the etiology of some overuse running injuries.

Collapse of the medial longitudinal arch (MLA) helps absorb energy through rotation of bones and deformation of the connective tissues, including the plantar fascia, plantar ligaments, and muscles/tendons (Ker et al., 1987; Yoshikawa et al., 1994). Other characteristics of viscoelasticity include: greater stiffness as strain rate increases; gradual decrease in tension over time with constant or repetitive force; and lengthening with constant or repetitive force (Nigg and Herzog, 1994, p. 117; Whiting and Zernicke, 2008, p. 90). After five contractions of the plantarflexors at 80% of maximum, tendon length increased about 5 mm and then plateaued for the next five contractions (Maganaris et al., 2002). Because of these tissue properties and possible material fatigue, it can be inferred that MLA stiffness will be greater during running than walking, and MLA deformation may increase after the cyclical loading of a long run.

Dynamic MLA deformation has been quantified during walking and running but not after a long run. During walking, arch height decreases about 11 to 15% or 5.3 to 8 mm and arch length increases about 2% or 4 mm (Cashmere et al., 1999; Cornwall and McPoil, 1999; Hunt et al., 2001; Nielsen et al., 2009; Yang et al., 1985). During running, arch height decreases up to 10 mm (Ker et al., 1987; Nachbauer and Nigg, 1992). Comparisons between

walking and running are difficult as various measurements and different references (sitting or standing) are used. Only one study compared walking and running and reported greater MLA collapse in running (McPoil and Cornwall, 2007), which is reasonable considering loading and triceps surae activity are greater in running.

Several changes occur with fatigue that may increase risk for injury, making it critical to understand the effect of these changes on normal running mechanics. Muscles decrease bone strain on the tensile side during bending, as demonstrated during heel rise (Sharkey et al., 1995). However, if muscles become fatigued during prolonged activity the risk for injury may increase as strains, strain rate, and bending moments increase (Arndt et al., 2002; Yoshikawa et al., 1994). Greater pressure under the metatarsal heads and reduced pressure under the toes after a marathon and fatiguing 30 minute run may be caused by fatiguing the toe flexors (Bisiaux and Moretto, 2008; Nagel et al., 2008). Additionally, increased peak pressure under the medial midfoot after running (Weist et al., 2004; Wu et al., 2007) support that there is greater deformation, or at least deformation velocity, of the arch which may also be linked to toe flexor fatigue. After fatiguing the intrinsic foot muscles (although extrinsic muscles were not monitored to determine specificity of the exercise), navicular drop increased from sit to stand (Headlee et al., 2008). This fatigue may have been present in dynamic activity also, although it was not tested. Contrarily, a 30 minute fatiguing run resulted in decreased medial midfoot pressure (Bisiaux and Moretto, 2008). Differences in plantar region definitions may account for these differences. Regardless, the effects of fatigue may alter normal arch mechanics and increase risk for injury.

MLA deformation after a long run may be greater due to material fatigue of passive tissues and decreased force production of the arch-supporting muscles, but this has yet to be

investigated using 3-D motion capture. The majority of running is at a comfortable intensity and not an exhausting race-pace, so it is probable injuries begin to develop after running a few miles at low to moderate intensities. Therefore, the purpose of the current study was to evaluate the changes in medial longitudinal arch mechanics before and after a 45 minute run at a comfortable pace. Specifically, changes in arch length, navicular displacement, arch height index, arch rigidity index, and arch quasi-stiffness. It was hypothesized there would be greater MLA deformation and decreased arch stiffness after the run. The secondary aim was to compare walking and running, for which it was hypothesized arch stiffness and MLA deformation would be greater during running than walking.

2. METHODS

Thirty recreational runners (15 men, 15 women) of similar age (mean (SD); men: 20.8 (2.1) yrs; women: 21.3 (1.9) yrs) and weekly mileage (men: 21 (12) mi; women: 20 (10) mi) were recruited for this study. The men (height: 1.77 (0.05) m; mass: 75.6 (10.2) kg; 1600 m time: 5:32 (28) sec) were significantly faster than the women (height: 1.66 (0.03) m; mass: 57.5 (5.9) kg; 1600 m time: 6:29 (24) sec). One woman and three men were forefoot strikers and the rest were rearfoot strikers. Participants were excluded if they had any lower extremity surgery, deformity, current pain, or wore prescribed foot orthotics. Inclusion criteria included a weekly mileage of 16.9 to 80.5 km (10 to 50 mi) and being capable of running a 5k in less than 25 minutes or 1600 m in less than 7.5 minutes. Experiment procedures were approved by the university Institutional Review Board and all participants gave their written informed consent to participate.

Participants visited the lab twice. On the first visit anthropometric measurements were taken which were used for joint moment calculations (Vaughan et al., 1992).

Participants completed a maximum effort 1600 m run, after which we recorded maximum heart rate and rating of perceived exertion (RPE). Seventy-percent of their 1600 m velocity was calculated and used as the speed for the 45 minute treadmill run and overground running trials during the second visit. Twelve participants (6 men, 6 women) were randomly selected for reliability testing performed on visit one, which tested the various measurements of arch mobility. Since participants performed these trials before the maximum effort 1600 m run so fatigue would not affect the values, we estimated their 1600 m time to determine the velocity for the running trials. Because of incomplete data, one female was eliminated from the reliability testing.

All participants did the same protocol on the second visit, which was 3 to 14 days later. Twelve retro-reflective markers were placed on the pelvis and right leg. Additional markers were placed on the right foot (Fig. 1) while participants stood with weight evenly distributed on a custom-built apparatus for foot measurements. Landmarks included the navicular tuberosity, first metatarsal (2 cm from the supporting surface), medial calcaneus (2 cm from the supporting surface) (Nielsen et al., 2009), dorsum at 50% total foot length (Williams and McClay, 2000), and posterior heel (2 cm from the supporting surface, in-line with the Achilles tendon). The medial calcaneal marker was placed 3 cm and 4 cm anterior from the most posterior aspect of the foot for females and males, respectively (Bandholm et al., 2008). The location of the foot/ankle markers were circled with permanent marker so markers could be replaced post-treadmill run. Eight infrared motion analysis cameras (Vicon, Oxford, UK) sampling at 200 Hz recorded marker position while ground reaction forces were collected simultaneously at 1000 Hz (AMTI, Watertown, MA, USA).



Figure 1. Reflective markers placed on the foot.

Barefooted, participants performed four pre-treadmill run conditions. First a static standing trial was recorded to define hip, knee, and ankle joint centers. Participants then sat on a chair (43 cm) with their sacrum at 75% of thigh length and only the right foot on the force platform. This seated condition was the reference condition for all other trials. The participants then walked at their preferred velocity (1.36 (0.19) m/s) while six successful trials (complete foot on force platform, no visual targeting, and within $\pm 5\%$ velocity) were collected. Finally, six running trials were collected at 70% of their 1600 m velocity. Participants were instructed to use the same foot-strike pattern as they use during shod runs.

Upon completing the overground running trials, the reflective markers on the foot were removed and participants put on their shoes. Treadmill speed was set to 70% of their 1600 m velocity and the participants ran for 45 minutes. Heart rate and RPE were recorded immediately after the run, participants removed their shoes, and the reflective foot markers were replaced on the foot in their original locations. Participants then completed the post-run conditions which were identical to the pre-run conditions but in reverse order. For the post-run running trials, participants continuously jogged between trials. Time was recorded from

the end of the treadmill run to the start of the first running trial, along with the heart rate after the first and last running trials.

Kinematic data were filtered with a fourth-order Butterworth filter using a low-pass cut-off frequency of 16 Hz. Ground reaction force data remained unfiltered. Matlab (Version 7.8.0 R2009a, Natick, MA, USA) was used to calculate all dependent variables. Stance phase data were interpolated to 101 points and every fifth frame of analog data was extracted to match kinematic sampling frequency. Medial longitudinal arch mechanics were measured by change in arch length, navicular height, arch height index (AHI), and arch stiffness. Arch length was defined as the 3-D distance between the medial calcaneus and first metatarsal markers. Navicular height was defined as the 3-D perpendicular distance from the navicular marker to the arch length line. We will refer to change in navicular height as navicular displacement. Change in arch length and navicular displacement were expressed as change from the seated trial with a positive value representing lengthening and lowering of the arch. The pre-run seated reference trial was used for all the pre-run conditions and the post-seated reference trial was used for the post-run conditions.

AHI was calculated as dorsal arch height at 50% of foot length divided by truncated foot length (Williams and McClay, 2000) but in 3-D. Dorsal arch height was taken from the dorsal foot marker to the bottom of the foot. Truncated foot length extended from a virtual marker 2 cm inferior to the posterior calcaneus marker to a virtual marker at the first metatarsal level, directly anterior to the posterior calcaneus and also 2 cm inferior. Change in AHI was the difference between seated AHI. Arch rigidity index (ARI) was the ratio of AHI_{stand}/AHI_{sit} (Richards et al., 2003).

Arch stiffness was estimated as the slope of the resultant ground reaction force by navicular displacement curve during both the collapse and the reformation of the arch. Arch collapse quasi-stiffness was calculated from 15% of stance (to eliminate impact peaks that did not contribute to navicular displacement) to maximum navicular displacement (~55% of stance for running). Arch reformation quasi-stiffness was calculated from maximum navicular displacement to 85% of stance.

All statistical tests were completed in SPSS (version 17.0, Chicago, IL, USA). Men and women were analyzed separately because gender differences have been reported (McPoil et al., 2009; Nielsen et al., 2009; Zifchock et al., 2006). A 2×2 repeated measures ANOVA with $\alpha=0.05$, was used to detect main effects and interactions between the two independent variables of time (pre-, post-run) and sex (men, women). A separate one-way repeated measures ANOVA was used to detect differences for walking versus running. For the reliability portion of the study, type (2,1) intra-rater intraclass correlation coefficients were calculated.

3. RESULTS

Men ran the maximum effort 1600 m significantly faster than women, which resulted in a faster 45 minute and overground running velocity (men: 3.40 (0.27) m/s; women: 2.88 (0.19) m/s). Heart rate after the 1600 m run (men: 191 (9) bpm; women: 186 (12) bpm) and RPE (men: 17.5 (1.1); women: 17.3 (1.7)), however, were not different. Heart rate and RPE after the 45 minute run were less than after the 1600 m (89% and 80%, respectively). Heart rate was similar after the first and last successful running trials (138 (17) bpm), which was an 18% decrease compared to heart rate after completing the treadmill run.

Two male participants were unable to complete the full 45 minutes (35:20 and 42:25 minutes). Visual assessment of their data did not reveal a significant difference from other participants, so they were included in the analysis.

Table 1
Intrarater intraclass correlation coefficients between visit 1 and 2

Condition	Arch length	Navicular height/ displacement	AHI/change in AHI	ARI	Arch collapse stiffness	Arch reformation stiffness
Sit ^a	0.778	0.770	0.753	0.432	--	--
Stand ^a	0.822	0.642	0.885	--	--	--
Walk ^b	0.870	0.924	0.586	--	--	--
Run ^b	0.915	0.726	0.681	--	0.818	0.929

^aSingle-measures ICCs. ^bAverage-measures ICCs. AHI=Arch Height Index; ARI=Arch Rigidity Index

Intrarater intraclass correlation coefficients (6 men, 5 women) are presented in Table 1. Arch length ranged from 0.778 to 0.915. Navicular height/displacement ranged from 0.642 to 0.924. AHI/change in AHI ranged from 0.586 to 0.885. ARI was 0.432 and dynamic arch stiffness ranged from 0.818 to 0.929. Ground reaction force during the sitting reference condition was not different between visits ($p=0.205$), so it does not account for the variability between visits. Because the reliability running trials on visit 1 were performed before the 1600 m run, we estimated their 1600 m time, but running velocity between visits was not significantly different ($p=0.283$) because runners both under- and over-estimated their time.

The gender \times time interaction for ARI was significant ($p=0.013$). ARI decreased post-run for men (0.953 (0.020) to 0.944 (0.019)) and increased post-run for women (0.945

(0.022) to 0.958 (0.018)). There were no main effects for either time or gender for any of the dependent variables.

To ensure the sitting reference trials were not significantly different before and after the 45 minute run, several variables were analyzed. Arch length, navicular height, dorsum height, truncated foot length, and ground reaction force were not significantly different pre- and post-run (all $p > 0.05$), so the reference trial appears unaffected by the run.

Table 2
Walking and running medial longitudinal arch deformation characteristics—Mean (SD)

Condition	Arch lengthening (mm)	Time to peak lengthening (% stance)	Navicular displacement (mm)	Time to peak displacement (% stance)	Change in AHI	Time to peak change AHI (% stance)
Walking	4.3 (1.5)	29 (10)	4.7 (1.8)	75 (8)	0.0235 (0.009)	62 (25)
Running	5.9 (2.0)*	40 (11)*	7.1 (2.1)*	55 (6)*	0.0280 (0.009)*	44 (17)*

*Significantly different from walking at $p < 0.05$.

Because there were no significant main effects, data (excluding ARI) were collapsed across gender to analyze differences between pre-run walking and running. Dependent variables for pre-run walking and running are shown in Table 2. Walking displaced the navicular by approximately 17% relative to the sitting position. This significantly increased to 26% during running. As the navicular collapsed during gait, the arch significantly lengthened (walking: 2.9%; running: 4.0%). The magnitude of these changes is shown in Figure 2.

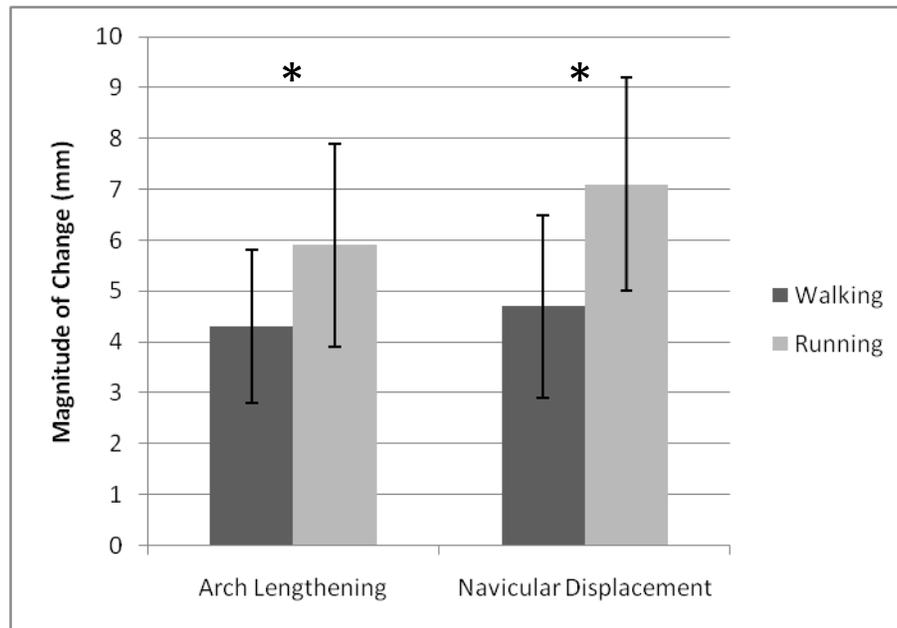


Figure 2. Pre-run mean (SD) arch lengthening and navicular displacement relative to sitting. * $p < 0.05$ between walking and running.

Time to maximum navicular displacement occurred later in stance for walking than running (75 (8)% versus 55 (6)%), and time to maximum arch lengthening occurred earlier in stance for walking (29 (10)% versus 40 (11%)) (Fig. 3). Change in AHI was less for walking than running (0.0235 (0.008) versus 0.0280 (0.009)) and time to peak change in AHI occurred later in stance for walking than running (62 (25)% versus 44 (17)%). This trend follows that of navicular displacement. During running, arch collapse quasi-stiffness was 142 (62) N/mm, and during the reformation of the arch it was 205 (70) N/mm. Dynamic arch stiffness was quantified only for running for two reasons: 1) stiffness was only quantified until 85% of stance and peak navicular displacement for walking occurred at about 75%, so arch reformation quasi-stiffness was based off one or two points sometimes, and 2) vertical ground reaction force during walking has two peaks but navicular displacement has one, so some arch collapse quasi-stiffness values were negative.

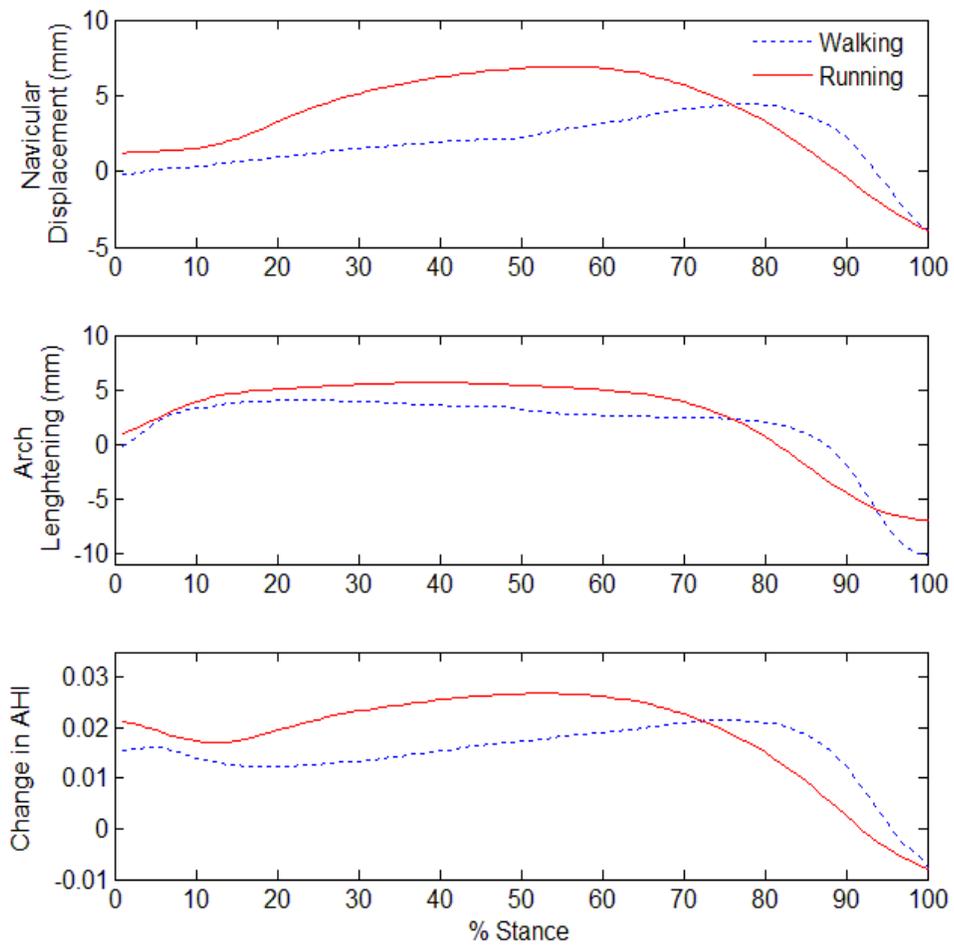


Figure 3. Ensemble curves for walking and running navicular displacement, arch lengthening, and change in AHI. The dotted line represents walking and the solid line represents running.

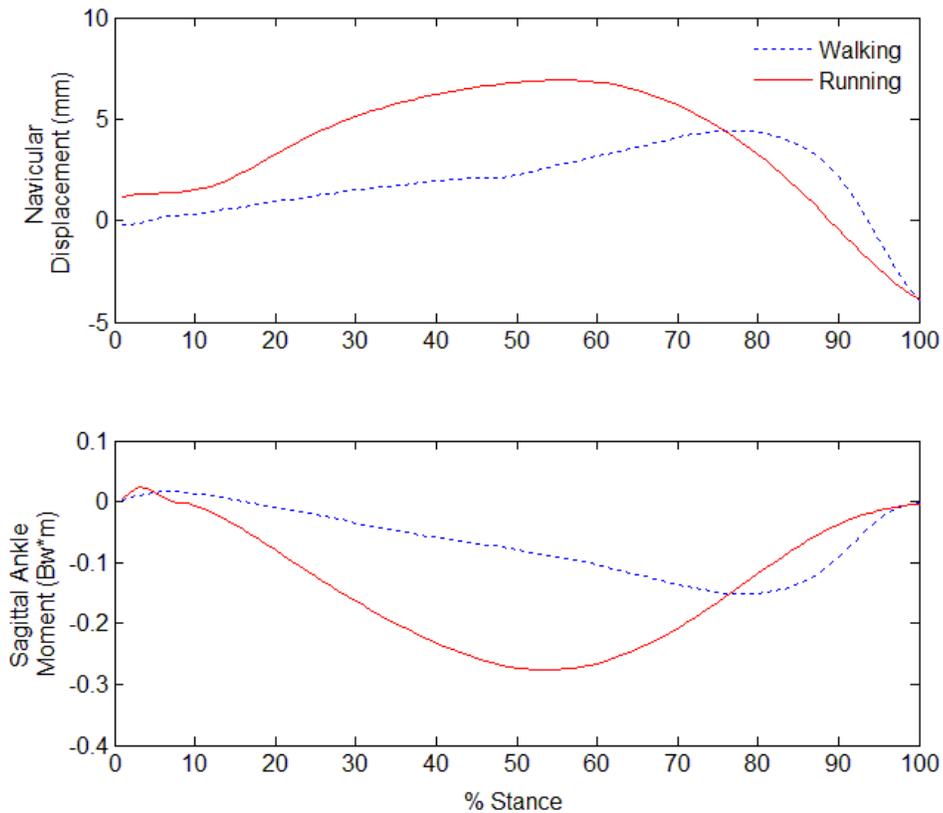


Figure 4. Ensemble curves for navicular displacement and sagittal ankle joint moment during walking and running. The dotted line represents walking and solid line represents running.

4. DISCUSSION

The purpose of the study was to compare walking and running arch mechanics and if they change after a 45 minute run. The first hypothesis that deformation would be greater and arch stiffness would decrease after the 45 minute run was not supported. However, our second hypothesis that arch deformation would be greater in running than walking was supported.

4.1 Reliability

The most reliable measurement depended on the activity, but arch length was consistently high (all ≥ 0.778), which is considered “substantial” to “almost perfect” (Landis and Koch, 1977). AHI was more reliable statically, which agrees with previous research

(Williams and McClay, 2000) but relatively unreliable dynamically, which does not agree with previous research (Franettovich et al., 2007). Surprisingly the dynamic measures were generally more reliable than the static measures. This may be a result of the multiple trials collected for the dynamic variables and using the “average-measures ICCs”. The ICCs were “almost perfect” for the new dynamic arch stiffnesses during running which warrants future examination.

4.2 Effect of prolonged running on men versus women

The interaction of gender and time for ARI is puzzling. This interaction suggests that men’s arches became more compliant after the run while women’s arches became stiffer. ARI is a measure of arch rigidity from sit to stand, but post-hoc analysis revealed no significant change in sitting or standing AHI for men or women, although the gender \times time interaction for sitting AHI was nearly significant ($p=0.061$) increasing for men and decreasing for women, which supports the interaction for ARI. Arch stiffness during the first half of stance followed a similar trend as ARI for gender but it lacked significance. Standing arch length, which is shorter than truncated foot length used in the AHI calculation, showed a significant gender \times time interaction ($p=0.022$), with arch length increasing 1 mm for men and decreasing 1 mm for women post-run. This would also result in the ARI results. Regardless, a 1 mm change may not have clinical importance.

4.3 Effect of prolonged running

Lack of changes in MLA deformation in the current study may be due to the lower intensity. Running velocity was 3.40 m/s for men and 2.88 m/s for women, post-run RPE was 14 (one above “somewhat hard”), and most participants said the treadmill speed was slower than their pace for long runs. Therefore, muscular or cardiovascular fatigue probably did not

occur. Our results concur with previous research that found no differences in plantar pressures or tibial accelerations after a 30 to 90 minute run (Deleu et al., 2010; Mizrahi et al., 1997; Schlee et al., 2009). Schlee et al. (2009) had participants run at a speed corresponding to a lactate concentration of 4 mmol/L, which is above ventilator anaerobic threshold and near maximum lactate steady state (Czuba et al., 2009; Green et al., 1983). Running velocity was self-selected in Deleu et al. (2010), but they did not report exertion level, making it difficult to compare to the current study. Mizrahi et al. (1997) had participants run at a speed corresponding to their anaerobic threshold (mean: 2.76 m/s), after which some participants showed signs of fatigue and others did not. The average running velocities in this study for men and women were faster than Mizrahi et al. (1997) but likely slower than Schlee et al. (2009). A lower exertion level in the current study may explain why longer or more intense exercise protocols found significant differences in plantar pressures and bone strain post-exercise (Arndt et al., 2002; Weist et al., 2004; Wu et al., 2007; Yoshikawa et al., 1994). Post-hoc correlations were calculated between exertion level (HR and RPE) and post-run MLA variables to investigate if post-run exertion influenced MLA mechanics, but no significant correlations were found.

It took on average a little over 3.5 minutes for participants to get off the treadmill and start their post-run running trials in the current study. In about 2 minutes after fatiguing posterior tibialis, isometric force increased from 67% to 80% of baseline (Pohl et al., 2010). Therefore, muscle recovery may have occurred during the transition from treadmill to overground running trials in the current study.

Additionally, other muscles or passive tissues may have compensated for lack of changes. After increased barefoot activity over four months, arch length decreased over 4 mm, which the authors suspected was due to increased intrinsic muscle activity (Robbins and Hanna, 1987). Because muscle activity was not monitored in the current study, changes in activation cannot be inferred.

It is possible that differences in arch collapse are masked by using the respective pre- and post- run reference sitting trial if the arch was collapsed more for the post-run sitting trial. However, the various arch measurements and ground reaction forces were not different during after the run, so lack of changes may be accounted for by the abovementioned factors.

4.4 Effect of gender

There was no main effect for gender. This does not support previous research that men have greater MLA collapse than women (although less than 1 mm difference) (McPoil et al., 2009; Nielsen et al., 2009). Despite non-significant differences in the current study, there was a trend towards greater navicular displacement, arch lengthening, and change in AHI in men than women. These slight differences disappeared after normalizing to seated values, supporting the importance of reporting relative values. Neither arch stiffness nor ARI were different between men and women in contrast to Zifchock et al. (2006), but there was a trend towards greater stiffness in men. The specific population (runners) in the current study may account for lack of significant differences between genders as tendon cross-sectional area has been shown to increase in trained runners versus non-runners (Rosager et al., 2002).

4.5 Walking versus running

The magnitude of changes in walking coincides with those previously reported (Cashmere et al., 1996; Hunt et al., 2001; Yang et al., 1985). Similarly, the pattern of arch

lengthening and change in arch height closely resemble previous studies (Caravaggi et al., 2010; Cashmere et al., 1996; Hunt et al., 2001). Peak arch lengthening occurred before midstance and navicular displacement peaked after heel rise. During running, however, navicular displacement occurred around midstance. This may be related to peak loading of the Achilles tendon, fascia, and plantar ligaments which occurred at about 70% of stance during walking and 60% during running (Giddings et al., 2000). For both walking and running, arch length and navicular displacement become negative at the end of stance, indicating a shortening and raising of the arch as the metatarsophalangeal joints dorsiflex and engage the windlass mechanism. Arch length became more negative for walking than running, likely reflecting greater dorsiflexion of the toes which may cause greater increase in plantar fascia tension.

Greater MLA deformation in running versus walking agrees with McPoil and Cornwall (2007). Considering other researchers found increased MLA collapse as weight and Achilles tendon force increases, this seems logical (Billis et al., 2007; Cheung et al., 2006; Ker et al., 1987; McPoil et al., 2009; Nielsen et al., 2009). In the current study, sagittal ankle joint moment during stance was highly correlated to navicular displacement during walking ($r=0.81$) and running ($r=0.89$) (Fig. 4). Sagittal ankle joint moment was 1.7 to 2 times greater for running than walking and navicular displacement was approximately 1.5 times greater for running. Contraction of the gastrocnemius and soleus pulls on the calcaneus and ground reaction force under the forefoot work together to cause dorsiflexion at the midfoot. However, Wolf et al. (2008) noted less rotation of the foot bones during slow running compared to walking. Therefore, MLA deformation may be a combination of viscoelastic stiffness, ground reaction force, and triceps surae force.

The influence of walking or running velocity on the magnitude of arch deformation was probably minimal because angular change of the MLA at slow to fast walking velocities (0.9 to 1.98 m/s) is less than 2° (Caravaggi et al., 2010). Likewise, arch deformation from vertical load and triceps surae tension begin to plateau with increasing load (Cheung et al., 2006). This may explain why significantly greater ground reaction forces from the men's larger mass and running velocity did not result in greater MLA deformation than women in the current study.

Interpretation of the results must be considered with the limitations of the study. One of the main limitations was the removal and replacement of reflective markers. The magnitude of arch collapse is very small, so inexact marker placement after the run may explain the lack of change. Secondly, skin artifact can be of the same magnitude as the changes observed (Maslen and Ackland, 1994; Tranberg and Karlsson, 1998). Thirdly, participants ran the 45 minutes shod but tested barefoot, which may under- or overestimate arch deformation during the actual run. MLA deformation may be greater when running barefoot, because somatosensory input indicates a more rigid surface and adapts by becoming more compliant (Robbins and Hanna, 1987), possibly by decreasing muscle tension.

5. CONCLUSIONS

In conclusion, medial longitudinal arch deformation did not change after a 45 minute run at a moderate intensity. The neuromuscular system may have compensated by recruiting different arch muscles as some became fatigued, or the arch may be resilient to the repetitive loading of a non-exhausting run. It is possible changes in mechanics that increase risk for injury did occur but were not measured. For example, the relationship between arch collapse

and both rearfoot motion and tibial rotation should be analyzed. Arch deformation was greater during running than walking. Therefore, it is important to do clinical assessments of arch motion during running, rather than walking, if that is the activity that is causing pain. Increased arch collapse during running is consistent with increased ground reaction forces and triceps surae forces. These forces and resulting sagittal ankle joint moment peak earlier in running than walking, which may also explain why peak navicular displacement occurs earlier in stance for running than walking. Future studies should quantify shod arch deformation to see if the foot responds differently. Shod analysis more precisely replicates how most runners run and would potentially eliminate any recovery time from completing the run to collecting trials. Additionally, analyzing arch motion after a more fatiguing run or longer duration (e.g., a marathon) may reveal significant changes.

REFERENCES

- Arndt, A., Ekenman, I., Westblad, P., and Lundberg, A. (2002). Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *Journal of Biomechanics*, 35(5), 621-8.
- Bandholm, T., Boysen, L., Haugaard, S., Kreutzfeldt Zebis, M., and Bencke, J. (2008). Foot medial longitudinal-arch deformation during quiet standing and gait in subjects with medial tibial stress syndrome. *The Journal of Foot and Ankle Surgery*, 47(2), 89-95.
- Billis, E., Katsakiori, E., Kapodistrias, C., Kapreli, E. (2007). Assessment of foot posture: Correlation between different clinical techniques. *The Foot*, 17, 65-72.
- Bisiaux, M. and Moretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait and Posture*, 28, 693–698.
- Caravaggi, P., Pataky, T., Gunther, M., Savage, R., and Crompton, R. (2010). Dynamics of longitudinal arch support in relation to walking speed: contribution of the plantar aponeurosis. *Journal of Anatomy*, 217, 254-61.
- Cashmere, T., Smith, R., and Hunt, A. (1999). Medial longitudinal arch of the foot: stationary versus walking measures. *Foot and Ankle International*, 20(2), 112-8.
- Cheung, J.T-M., Zhang, M., and An, K-N. (2006). Effect of Achilles tendon loading on plantar fascia tension in the standing foot. *Clinical Biomechanics*, 21, 194–203.
- Cornwall, M. and McPoil, T. (1999). Relative movement of the navicular bone during normal walking. *Foot and Ankle International*, 20, 507–512.
- Czuba, M., Zając, A., Cholewa, J., Poprzęcki, S., Waśkiewicz, Z, and Mikołajec, K. (2009). Lactate threshold (D-max method) and maximal lactate steady state in cyclists. *Journal of Human Kinetics*, 21, 49-56.
- Deleu, P.A., Deschamps, K., Leemrijse, T., Matricali, G. (2010). Impact of 90 minutes running exercise on plantar loading of the forefoot: A prospective study on symptom-free athletes. *Journal of Bone and Joint Surgery (British Volume)*, 92-B(Supp 4), 585.
- Giddings, V.L., Beaupre, G.S., Whalen, R.T., and Carter, D.R. (2000). Calcaneal loading during walking and running. *Medicine and Science in Sports and Exercise*, 32(3), 627-634.
- Green, H.J., Hughson, R.L., Orr, G.W., and Ranney, D.A. (1983). Anaerobic threshold, blood lactate, and muscle metabolites in progressive exercise. *Journal of Applied Physiology*, 54, 1032-1038.

- Headlee, D., Leonard, J., Hart, J., Ingersoll, C., and Hertel, J. (2008). Fatigue of the plantar intrinsic foot muscles increases navicular drop. *Journal of Electromyography and Kinesiology*, 18, 420-425.
- Hunt, A.E., Smith, R.M., Torode, M, and Keenan, A.M. (2001). Inter-segment foot motion and ground reaction forces over the stance phase of walking. *Clinical Biomechanics (Bristol, Avon)*, 16, 592-600.
- Ker, R., Bennett, M., Bibby, S.R., Kester, R.C., and Alexander, R. (1987). The spring in the arch of the human foot. *Nature*, 325, 147-49.
- Landis, J.R. and Koch, G.G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159-174.
- Maganaris, C.N., Baltzopoulos, V., and Sargeant, A.J. (2002). Repeated contractions alter the geometry of human skeletal muscle. *Journal Applied Physiology*, 93, 2089-2094.
- Maslen, B. and Ackland, T. (1994). Radiographic study of the skin displacement errors in the foot and ankle during standing. *Clinical Biomechanics*, 9, 291-6.
- McPoil, T.G. and Cornwall, M.W. (2007). Prediction of dynamic foot posture during running using the longitudinal arch angle. *Journal of the American Podiatric Medicine Association*, 97(2), 102-107.
- McPoil, T.G., Vicenzino, B., Cornwall, M.W., Collins, N., and Warren, M. (2009). Reliability and normative values for the foot mobility magnitude: a composite measure of vertical and medial-lateral mobility of the midfoot. *Journal of Foot and Ankle Research*, 2:6.
- Mizrahi, J., Voloshin, A., Russek, D., Verbitsky, O., and Isakov, E. (1997). The influence of fatigue on EMG and impact acceleration in running. *Basic and Applied Myology*, 7(2), 111-118.
- Nachbauer, W. and Nigg, B.M. (1992). Effects of arch height of the foot on ground reaction forces in running. *Medicine in Science and Sports Medicine*, 24(11), 1264-9.
- Nagel, A., Ferfnholz, F., Kibele, C., and Rosenbaum, D. (2008). 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.
- Nielsen, R., Rathleff, M., Simonsen, O., and Langberg, H. (2009). Determination of normal values for navicular drop during walking: A new model correcting for foot length and gender. *Journal of Foot and Ankle Research*, 2, 12-18.
- Nigg, B.M. and Herzog, W. (Eds.). (1994). *Biomechanics of the Musculoskeletal System*. West Sussex, England: John Wiley and Sons, p. 117.

- Pohl, M.B. and Buckley J.G. (2008). Changes in foot and shank coupling due to alterations in foot strike pattern during running. *Clinical Biomechanics*, 23, 334-41.
- Pohl, M.B., Rabbito, M., and Ferber, R. (2010). The role of tibialis posterior fatigue on foot kinematics during walking. *Journal of Foot and Ankle Research*, 3:6.
- Richards, C.J., Card, K., Song, J., Hillstrom, H., Butler, R., and Davis, I.M. (2003). A novel arch height index measurement system (AHIMS): Intra- and inter-rater reliability. *Proceedings of the American Society of Biomechanics 26th Annual Meeting*.
- Robbins, S.E. and Hanna, A.M. (1987). Running-related injury prevention through barefoot adaptation. *Medicine and Science in Sports and Exercise*, 19(2), 148-156.
- Rosager, S., Aagaard, P., Dyhre-Poulsen, P., Neergaard, K., Kjaer, M., and Magnusson, S.P. (2002). Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scandinavian Journal of Medicine and Science in Sports*, 12(2), 90-98.
- Schlee, G., Milani, T., and Roemer, K. (2009). Plantar pressure distribution, rearfoot motion and ground reaction force after long distance running. *Footwear Science*, 1(3), 129-134.
- Sharkey, N.A., Ferris, L., Smith, T.S., and Matthews, D.K. (1995). Strain and loading of the second metatarsal during heel-lift. *Journal of Bone and Joint Surgery (American)*, 77(7), 1050-7.
- Tranberg, R. and Karlsson, D. (1998). The relative skin movement of the foot: a 2-D roentgen photogrammetry study. *Clinical Biomechanics*, 13, 71-6.
- Vaughan, C.L., Davis, B.L., and O'Connors, J.C. (1992). *Dynamics of Human Gait*. Human Kinetics, Champaign, IL.
- Weist, R., Eils, E., and Rosenbaum, D. (2004). The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *American Journal of Sports Medicine*, 32(8), 1893-98.
- Whiting, W. and Zernicke, R. (2008). *Biomechanics of musculoskeletal injury* (2nd ed.). United States of America: Human Kinetics, p. 90.
- Williams, D.S. and McClay, I.S. (2000). Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. *Physical Therapy*, 80(9), 864-71.
- Wolf, P., Stacoff, A., Liu, A., Nester, C., Arndt, A., Lundberg, A., and Stuessi, E. (2008). Functional units of the human foot. *Gait and Posture*, 28, 434-441.

Wu, W.L., Chang, J.J., Wu, J.H., Guo, L.Y., and Lin, H.T. (2007). EMG and Plantar Pressure Patterns after Prolonged Running. *Biomedical Engineering: Applications, Basis and Communications*, 19(6), 383-388.

Yang, S.M., Kayano, J., Norimatsu, T. Fujita, M., Matsusaka, N., and Suzuki, R. (1985). Dynamic changes of the arches of the foot during walking, in: *Biomechanics IX-A*, Winter, D.A., Norman, R.W., Wells, R.P., Hayes, K.C., and Patla, A.E. (Eds.). Champaign, IL: Human Kinetics Publishers, pp. 417-422.

Yoshikawa, T., Mori, S., Santiesteban, A.J., Sun, T.C., Hafstad, E., Chen, J., and Burr, D.B. (1994). The effects of muscle fatigue on bone strain. *Journal of Experimental Biology*, 188, 217-233.

Zifchock, R.A., Davis, I., Hillstrom, H., and Song, J. (2006). The effect of gender, age, and lateral dominance on arch height and arch stiffness. *Foot and Ankle International*, 27(5), 367-72.

CHAPTER 4. GENERAL CONCLUSIONS

Medial longitudinal arch collapse was investigated after a long run to see if any changes in mechanics were related to possible injury mechanisms. However, neither the magnitude of collapse nor dynamic arch stiffness changed after the moderate intensity run. It is possible the arch-supporting muscles were not fatigued within 45 minutes and the cyclical loading had little effect on the passive structures. Even if muscular fatigue did occur, the neuromuscular system could have recruited other muscles so as to not compromise arch integrity.

Arch deformation appears to result from several factors. First, vertical ground reaction force deforms the arch but is more effective later in stance when only the forefoot is in contact with the ground. Second, Achilles tendon forces pull on the calcaneus, lengthening the arch. Lastly, viscoelastic strain rate influences the magnitude of deformation, but to a lesser extent. Opposing the deforming forces are the tensile forces of the plantar fascia, plantar ligaments, tibialis posterior, digit flexors, and other smaller intrinsic muscles. Ground reaction forces and triceps surae forces are greater in running than walking, which explains the greater deformation. As such, tensile forces in the tissues resisting this collapse increase, which has previously been estimated. Because force magnitudes and loading frequency are greater during running, this may explain why injuries are much more common from running than walking.

Future studies should quantify shod arch deformation using fluoroscopy to see if the foot responds differently. Shod analysis more precisely replicates how most runners run and would potentially eliminate any recovery time from completing the run to collecting trials. Additionally, analyzing arch motion after a more fatiguing run or longer duration (e.g., a

marathon) may reveal significant changes, as suggested by some plantar pressure studies. EMG may indicate if fatigue of the triceps surae or arch-supporting muscles does occur, and if other muscles are recruited to compensate. However, the arch-supporting muscles (e.g., posterior tibialis, flexor digitorum longus) are deep and would require fine-wire EMG which would be hard to monitor over a long run. Finally, changes may have occurred over the 45 minute run in the current study that increased risk for injury, but were not measured. Because injuries have been associated with excessive or delayed pronation and internal tibial rotation, the relationship between these variables and arch collapse may reveal a plausible injury mechanism.

COMPLETE REFERENCE LIST

- Arndt, A., Ekenman, I., Westblad, P., and Lundberg, A. (2002). Effects of fatigue and load variation on metatarsal deformation measured in vivo during barefoot walking. *Journal of Biomechanics*, 35(5), 621-8.
- Arndt, A., Wolf, P., Liu, A., Nester, C., Stacoff, A., Jones, R., Lundgren, P., and Lundberg, A. (2007). Intrinsic foot kinematics measured in vivo during the stance phase of slow running. *Journal of Biomechanics*, 40(12), 2672-2678.
- Bandholm, T., Boysen, L., Haugaard, S., Kreutzfeldt Zebis, M., and Bencke, J. (2008). Foot medial longitudinal-arch deformation during quiet standing and gait in subjects with medial tibial stress syndrome. *The Journal of Foot and Ankle Surgery*, 47(2), 89-95.
- Barber Foss, K.D., Ford, K.R., Myer, G.D., and Hewett, T.E. (2009). Generalized joint laxity associated with increased medial foot loading in female athletes. *Journal of Athletic Training*, 44(4), 356-362.
- Barnes, A., Wheat, J., and Milner, C. (2008). Association between foot type and tibial stress injuries: a systematic review. *British Journal of Sports Medicine*, 42(2), 93-8.
- Basmajian, J. and Stecko, G. (1963). The role of muscles in support of the arch of the foot. *Journal of Bone and Joint Surgery*, 45, 1184-90.
- Beckett, M.E., Massie, D.L., and Bowes, K.D. (1992). Incidence of hyperpronation in the ACL injured knee. *Journal of Athletic Training*, 27(1), 58-60.
- Bellchamber, T.L. and van den Bogert, A.J. (2000). Contributions of proximal and distal moments to axial tibial rotation during walking and running. *Journal of Biomechanics*, 33, 1397-1403.
- Bennett, J.E., Reinking, M.F., Pluemer, B., Pentel, A., Seaton, M., and Killian, C. (2001). Factors contributing to the development of medial tibial stress syndrome in high school runners. *Journal of Orthopaedic and Sports Physical Therapy*. 31(9), 504-10.
- Billis, E., Katsakiori, E., Kapodistrias, C., and Kapreli, E. (2007). Assessment of foot posture: Correlation between different clinical techniques. *The Foot*, 17, 65-72.
- Bisiaux, M. and Moretto, P. (2008). The effects of fatigue on plantar pressure distribution in walking. *Gait and Posture*, 28, 693-698.
- Bouché, R.T. and Johnson, C.H. (2007). Medial tibial stress syndrome (tibial fasciitis): A proposed pathomechanical model involving fascial traction. *Journal of the American Podiatric Medical Association*, 97(1), 31-36.

- Bovens, A.M.P, Janssen, G.M.E., Vermeer, H.G.W., Hoeberigs, J.H., Janssen, M.P.E., and Verstappen, F.T.J. (1989). Occurrence of Running Injuries in Adults Following a Supervised Training Program. *International Journal of Sports Medicine*, 10, S186-S190.
- Brody, D.M. (1982). Techniques in the evaluation and treatment of the injured runner. *The Orthopedic Clinics of North America*, 13, 541-58.
- Burns, J., Keenan, A-M., and Redmond, A. (2005a). Foot type and overuse injury in triathletes. *Journal of the American Podiatric Medical Association*, 95(3), 235-241.
- Cain, L.E., Nicholson, L.L., Adams, R.D., and Burns, J. (2007). Foot morphology and foot/ankle injury in indoor football. *Journal of Science and Medicine in Sport*, 10(5), 311-319.
- Caravaggi, P., Pataky, T., Gunther, M., Savage, R., and Crompton, R. (2010). Dynamics of longitudinal arch support in relation to walking speed: Contribution of the plantar aponeurosis. *Journal of Anatomy*, 217, 254-61.
- Cashmere, T., Smith, R., and Hunt, A. (1999). Medial longitudinal arch of the foot: Stationary versus walking measures. *Foot and Ankle International*, 20(2), 112-8.
- Cheung, J.T-M., Zhang, M., and An, K-N. (2006). Effect of Achilles tendon loading on plantar fascia tension in the standing foot. *Clinical Biomechanics*, 21, 194-203.
- Cheung, R.T.H. and Ng, G.Y.F. (2008). Influence of different footwear on force of landing during running. *Physical Therapy*, 88(5), 620-628.
- Chuckpaiwong, B., Nunley, J.A., Mall, N.A., and 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.
- Clement, D.B., Taunton, J.E., Smart, G.W. (1984). Achilles tendinitis and peritendinitis: Etiology and treatment. *American Journal of Sports Medicine*, 12(3), 179-184.
- Close, J.R., Inman, V.T., Poor, P.M., and Todd, F.N. (1967). The function of the subtalar joint. *Journal of Clinical Orthopaedics*, 50, 159-79.
- Cornwall, M. and McPoil, T. (1999). Relative movement of the navicular bone during normal walking. *Foot and Ankle International*, 20, 507-512.
- Cowan, D., Jones, B., and Robinson, J. (1993). Foot morphologic characteristics and risk of exercise-related injury. *Archives of Family Medicine*, 2, 773-7.

Czuba, M., Zajęc, A., Cholewa, J., Poprzęcki, S., Wańkiewicz, Z., and Mikołajec, K. (2009). Lactate threshold (D-max method) and maximal lactate steady state in cyclists. *Journal of Human Kinetics*, 21, 49-56.

Dahle, L., Mueller, M., Delitto, A., and Diamond, J. (1991). Visual assessment of foot type and relationship of foot type to low extremity injury. *Journal of Orthopaedic Sports and Physical Therapy*, 14, 70-74.

Davis, I.S., Bowser, B., and Mullineaux, D. (2010). Do impacts cause running injuries? A prospective investigation. *Proceedings of the American Society of Biomechanics 34th Annual Meeting*.

Deleu, P.A., Deschamps, K., Leemrijse, T., Matricali, G. (2010). Impact of 90 minutes running exercise on plantar loading of the forefoot: a prospective study on symptom-free athletes. *Journal of Bone and Joint Surgery (British Volume)*, 92-B(Supp 4), 585.

Derrick, T.R., Dereu, D., and McLean, S.P. (2002). Impacts and kinematic adjustments during an exhaustive run. *Medicine and Science in Sports and Exercise* 34(6), 998-1002.

Donahue, S.W. and Sharkey, N.A. (1999). Strains in the metatarsals during the stance phase of gait: Implications for stress fractures. *The Journal of Bone and Joint Surgery*, 81, 1236-44.

Elftman, H. (1960). The transverse tarsal joint and its control. *Journal of Clinical Orthopaedics*, 16, 41-46.

Erdemir, A., Hamel, A.J., Fauth, A.R., Piazza, S.J., and Sharkey, N.A. (2004). Dynamic loading of the plantar aponeurosis in walking. *The Journal of Bone and Joint Surgery (American)*, 86, 546-552.

Ferber, R., Hreljac, A., and Kendall, K.D. (2009). Suspected mechanisms in the cause of overuse running injuries: a clinical review. *Athletic Training*, 1(3), 242-6.

Folkowski, P., Brunt, D., Bishop, M., Woo, R., Horodyski, M.B. (2003). Intrinsic pedal musculature support of the medial longitudinal arch: an electromyography study. *The Journal of Foot and Ankle Surgery*, 42(6), 327-33.

Flynn, J.M., Holmes, J.D., and Andrews, D.M. (2004). The effect of localized leg muscle fatigue on tibial impact acceleration. *Clinical Biomechanics*, 19(7), 726-732.

Franettovich, M., Chapman, A., and Vicenzino, B. (2008). Tape that increases medial longitudinal arch height also reduces leg muscle activity: a preliminary study. *Medicine and Science in Sports and Exercise*, 40, 593-600.

- Franettovich, M., McPoil, T., Russell, T., Skardoon, G., and Vicenzino, B. (2007). The ability to predict dynamic foot posture from static measurements. *Journal of the American Podiatric Medical Association*, 97(2), 115-120.
- Fredericson, M. and Misra, A.K. (2007). Epidemiology and aetiology of marathon running injuries. *Sports Medicine*, 37(4-5), 437-439.
- Frey, C. (1997). Footwear and stress fractures. *Clinics in Sports Medicine*, 16(2), 249-257.
- Friesenbichler, B. Stirling, L.M., Federolf, P., and Nigg, B.M. (2010). Tissue vibration in prolonged running. *Journal of Biomechanics*, DOI: 10.1016/j.jbiomech.2010.08.034.
- Gefen, A. (2003). The in vivo elastic properties of the plantar fascia during the contact phase of walking. *Foot and Ankle International*, 24(3), 238-44.
- Geideman, W.M. and Johnson, J.E. (2000). Posterior Tibial Tendon Dysfunction. *Journal of Orthopaedic and Sports Physical Therapy*, 30 (2), 68-77.
- Gellman, R. and Burns, S. (1996). Walking aches and running pains: Injuries of the foot and ankle. *Primary Care*, 23(2), 263-80.
- Gerlach, K.E., White, S.C., Burton, H.W., Dorn, J.M., Leddy, J.J., and Horvath, P.J. (2005). Kinetic changes with fatigue and relationship to injury in female runners. *Medicine and Science in Sports and Exercise*, 37(4), 657-63.
- Giddings, V.L., Beaupre, G.S., Whalen, R.T., and Carter, D.R. (2000). Calcaneal loading during walking and running. *Medicine and Science in Sports and Exercise*, 32(3), 627-634.
- Green, H.J., Hughson, R.L., Orr, G.W., and Ranney, D.A. (1983). Anaerobic threshold, blood lactate, and muscle metabolites in progressive exercise. *Journal of Applied Physiology*, 54, 1032-1038.
- Gross, M.L., Davlin, L.B., Evanski, P.M. (1991). Effectiveness of orthotic shoe inserts in the long-distance runner. *American Journal of Sports Medicine*, 19(4), 409-412.
- Hamill, J. and Knutzen, K.M. (2003). *Biomechanical Basis of Human Movement* (2nd ed.). Lippincott Williams and Wilkins, pp. 207-214, 414, 432.
- Headlee, D., Leonard, J., Hart, J., Ingersoll, C., and Hertel, J. (2008). Fatigue of the plantar intrinsic foot muscles increases navicular drop. *Journal of Electromyography and Kinesiology*, 18, 420-425.
- Hicks, J.H. (1954). The mechanics of the foot. II. The plantar aponeurosis and the arch. *Journal of Anatomy*, 88, 25-30.

Hintermann, B. and Nigg, B.M. (1998). Pronation in runners: Implications for injuries. *Sports Medicine*, 26(3), 169-176.

Huang, C.K., Kitaoka, H.B., An, K.N., and Chao, E.Y. (1993). Biomechanical evaluation of longitudinal arch stability. *Foot and Ankle*, 14(6), 353-357.

Hunt, A.E., Smith, R.M., Torode, M., and Keenan, A.M. (2001). Inter-segment foot motion and ground reaction forces over the stance phase of walking. *Clinical Biomechanics (Bristol, Avon)*, 16, 592-600.

Inman, V.T. (1976). *The Joints of the Ankle*. Baltimore: Williams and Wilkins.

Jam B. (2006). Evaluation and retraining of the intrinsic foot muscles for pain syndromes related to abnormal control of pronation. Advanced Physical Therapy Education Institute. <http://www.aptei.com/articles/pdf/IntrinsicMuscles.pdf>. Accessed November, 11, 2010.

Jonson, S.R. and Gross, M.T. (1997). Intraexaminer reliability, interexaminer reliability, and mean values for nine lower extremity skeletal measures in healthy naval midshipmen. *Journal of Orthopaedic and Sports Physical Therapy*, 25, 253-63.

Kamanli, A., Sahin, S., Ozgocmen, S., Kavuncu, V., and Ardicoglu, O. (2004). Relationship between foot angles and hypermobility scores and assessment of foot types in hypermobile individuals. *Foot and Ankle International*, 25(2), 101-6.

Kanatli, U., Gozil, R., Besli, K., Yetkin, H., and Bolukbasi, S. (2006). The relationship between the hindfoot angle and the medial longitudinal arch of the foot. *Foot and Ankle International*, 27(8), 623-27.

Kastelic, J. and Baer, E. (1980). Deformation in tendon collagen. *Symposia of the Society for Experimental Biology*, 34, 397-435.

Kaufman, K.R., Brodine, S.K., Shaffer, R.A., Johnson, C.W., and Cullison, T.R.. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. *American Journal of Sports Medicine*, 27(5), 585-593.

Kayano, J. (1986). Dynamic function of the medial foot arch. *Nippon Seikeigeka Gakki Zasshi*, 60, 1147-1156.

Kaye, R.A. and Jahss, M.H. (1991). Tibialis posterior: a review of anatomy and biomechanics in relation to support of the medial longitudinal arch. *Foot and Ankle*, 11, 244-247.

Ker, R., Bennett, M., Bibby, S.R., Kester, R.C., and Alexander, R. (1987). The spring in the arch of the human foot. *Nature*, 325, 147-49.

- Kirby, K.A. (2000). Biomechanics of the normal and abnormal foot. *Journal of the American Podiatric Medical Association*, 90(1), 30-34.
- Korpelainen, R., Orava, S., Karpakka, J., Siira, P., and Hulkko, A. (2001). Risk factors for recurrent stress fractures in athletes. *American Journal of Sports Medicine*, 29, 304-10.
- Landis, J.R. and Koch, G.G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159–174.
- Latash, M.L. and Zatsiorsky, V.M. (1993). Joint stiffness: Myth or reality? *Human Movement Science*, 12, 653-92.
- Lees, A., Lake, M., and Klenerman, L. (2005). Shock absorption during forefoot running and its relationship to medial longitudinal arch height. *Foot and Ankle International*, 26, 1081-8.
- Loudon, J.K., Jenkins, W., and Loudon, K.L. (1996). The relationship between static posture and ACL injury in female athletes. *Journal of Orthopaedic and Sports Physical Therapy*, 24(2), 91-7.
- Lutter, L.D. (1980). Foot-related knee problems in the long distance runner. *Foot and Ankle*, 1, 112-116.
- Macera, C.A., Pate, R.R., Powell, K.E., Jackson, K.L., Kendrick, J.S., and Craven, T.E. (1989). Predicting lower-extremity injuries among habitual runners. *Archives of Internal Medicine*, 149(11), 2565-2568.
- Maganaris, C.N., Baltzopoulos, V., and Sargeant, A.J. (2002). Repeated contractions alter the geometry of human skeletal muscle. *Journal Applied Physiology*, 93, 2089-2094.
- Mann, R. and Inman, V.T. (1964). Phasic activity of intrinsic muscles of the foot. *Journal of Bone and Joint Surgery (American)*, 46, 469-481.
- Markolf, K.L., Mensch, J.S., and Amstutz, H.C. (1976). Stiffness and laxity of the knee—the contributions of the supporting structures. A quantitative in vitro study. *Journal of Bone and Joint Surgery (American)*, 5, 583-594.
- Maslen, B. and Ackland, T. (1994). Radiographic study of the skin displacement errors in the foot and ankle during standing. *Clinical Biomechanics*, 9, 291-6.
- Mathieson, I., Upton, D., and Prior, T.D. (2004). Examining the validity of selected measures of foot type: a preliminary study. *Journal of the American Podiatric Medical Association*, 94(3), 275-281.
- McPoil, T. and Cornwall, M. (2005). Use of the longitudinal arch angle to predict dynamic

foot posture in walking. *Journal of the American Podiatric Medicine Association*, 95(2), 114-120.

McPoil, T. and Cornwall, M. (2007). Prediction of dynamic foot posture during running using the longitudinal arch angle. *Journal of the American Podiatric Medicine Association*, 97(2), 102-107.

McPoil, T.G. and Cornwall, M.W. (1994). Relationship between neutral subtalar joint position and pattern of rearfoot motion during walking. *Foot and Ankle International*, 15(3), 141-5.

McPoil, T.G. and Cornwall, M.W. (2006). Use of plantar contact area to predict medial longitudinal arch height during walking. *Journal of the American Podiatric Medical Association*, 96(6), 489-494.

McPoil, T.G., Cornwall, M.W., Medoff, L., Vicenzino, B., Forsberg, K., and Hilz, D. (2008a). Arch height change during sit-to-stand: an alternative for the navicular drop test. *Journal of Foot and Ankle Research*, 1:3.

McPoil, T.G., Cornwall, M.W., Vicenzino, B., Teyhen, D.S., Molloy, J., Christie, D., and Collins, N. (2008b). Effect of using truncated versus total foot length to calculate the arch height ratio. *The Foot*, 18(4), 220-7.

McPoil, T.G., Vicenzino, B., Cornwall, M.W., Collins, N., and Warren, M. (2009). Reliability and normative values for the foot mobility magnitude: a composite measure of vertical and medial-lateral mobility of the midfoot. *Journal of Foot and Ankle Research*, 2:6.

Menz, H.B. (1998). Alternative techniques for the clinical assessment of foot pronation. *Journal of the American Podiatric Medicine Association*, 88, 119–129.

Michelson, J.D., Durant, D.M., and McFarland, E. (2003). Injury risk associated with pes planus in athletes. *Foot and Ankle International*, 23 (7), 629–933.

Milani, T.L., Hennig, E.M., and Lafortune, M.A. (1997). Perceptual and biomechanical variables for running in identical shoe constructions with varying midsole hardness. *Clinical Biomechanics*, 12(5), 294-300.

Mizrahi, J., Verbitsky, O., and Isakov, E. (2000a). Fatigue-related loading imbalance on the shank in running: A possible factor in stress fractures. *Annals of Biomedical Engineering*, 28, 463-469.

Mizrahi, J., Verbitsky, O., Isakov, E., and Daily, D. (2000b). Effect of fatigue on leg kinematics and impact acceleration in long distance running. *Human Movement Science*, 19, 139-151.

- Mizrahi, J., Voloshin, A., Russek, D., Verbitsky, O., and Isakov, E. (1997). The influence of fatigue on EMG and impact acceleration in running. *Basic and Applied Myology*, 7(2), 111-118.
- Murley, G., Menz, H., and Landorf, K. (2009b). Foot posture influences the electromyographic activity of selected lower limb muscles during gait. *Journal of Foot and Ankle Research*, 2, 35-43.
- Murley, G.S., Buldt, A.K., Trump, P.J., and Wickham, J.B. (2009a). Tibialis posterior EMG activity during barefoot walking in people with neutral foot posture. *Journal of Electromyography and Kinesiology*, 19(2), 69-77.
- Nachbauer, W. and Nigg, B.M. (1992). Effects of arch height of the foot on ground reaction forces in running. *Medicine in Science and Sports Medicine*, 24(11), 1264-9.
- Nagel, A., Ferfnholz, F., Kibele, C., and Rosenbaum, D. (2008). 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.
- Nakhaee, Z., Rahimi, A., Abaee, M., Rezasoltani, A. and Kalantari, K.K. (2008). The relationship between the height of the medial longitudinal arch (MLA) and the ankle and knee injuries in professional runners. *Foot (Edinburgh, Scotland)*, 18(2), 84-90.
- Nester, C.J., Liu, A.M., Ward, E., Howard, D., Cocheba, J., and Derrick, R. (2010). Error in the description of foot kinematics due to violation of rigid body assumptions. *Journal of Biomechanics*, 43(4), 666-672.
- Nielsen, R., Rathleff, M., Simonsen, O., and Langberg, H. (2009). Determination of normal values for navicular drop during walking: A new model correcting for foot length and gender. *Journal of Foot and Ankle Research*, 2, 12-18.
- Nigg, B.M. and Herzog, W. (Eds.). (1994). *Biomechanics of the Musculoskeletal System*. West Sussex, England: John Wiley and Sons, p. 117.
- Nigg, B.M., Cole, G.K., and Nachbauer, W. (1993). Effects of arch height of the foot on angular motion of the lower extremities in running. *Journal of Biomechanics*, 26(8), 909-916.
- Nilsson, J. and Thorstensson, A. (1989). Ground reaction forces at different speeds of human walking and running. *Acta Physiologica Scandinavica*, 136(2), 217-227.
- Ogon, M., Aleksiev, A.R., Pope., M.H., Wimmer, C., and Saltzman, C.L. (1999). Does arch height affect impact loading at the lower back level in running? *Foot and Ankle International*, 20, 263-66.

Pataky, T.C., Caravaggi, P., Savage, R., Parker, D., Goulermas, J.Y., Sellers, W.I., and Crompton, R.H. (2008). New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM). *Journal of Biomechanics*, 41(9), 1987-94.

Perry, J. (1992). *Gait Analysis -Normal, and Pathological Function*. Thorofare, NJ: Slack, Inc., pp. 51–87.

Plisky, M.S., Rauh, M.J., Heiderscheidt, B., Underwood, F.B., and Tank, R.T. (2007). Medial tibial stress syndrome in high school cross-country runners: Incidence and risk factors. *Journal of Orthopaedic and Sports Physical Therapy*, 37(2), 40-47.

Pohl, M.B. and Buckley J.G. (2008). Changes in foot and shank coupling due to alterations in foot strike pattern during running. *Clinical Biomechanics*, 23, 334-41.

Pohl, M.B., Hamill, J., and Davis, I.S. (2009). Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clinical Journal of Sport Medicine*, 19(5), 372-6.

Pohl, M.B., Rabbito, M., and Ferber, R. (2010). The relationship between static arch rigidity and foot kinematics during gait. *Proceedings of the 2nd Congress of the International Foot and Ankle Biomechanics Community*.

Pohl, M.B., Rabbito, M., and Ferber, R. (2010). The role of tibialis posterior fatigue on foot kinematics during walking. *Journal of Foot and Ankle Research*, 3:6.

Razeghi, M. and Batt, M.E. (2002). Foot type classification: A critical review of current methods. *Gait and Posture*, 15(3), 282-291.

Reber, L., Perry, J., and Pink, M. (1993). Muscular control of the ankle in running. *American Journal of Sports Medicine*, 21(6), 805-10.

Remvig, L., Jensen, D., and Ward, R. (2007). Epidemiology of general joint hypermobility and basis for the proposed criteria for benign joint hypermobility syndrome: Review of the literature. *The Journal of Rheumatology*, 34(4), 804-9.

Richards, C.J., Card, K., Song, J., Hillstrom, H., Butler, R., and Davis, I.M. (2003). A novel arch height index measurement system (AHIMS): Intra- and inter-rater reliability. *Proceedings of the American Society of Biomechanics 26th Annual Meeting*.

Riegger, C.L. (1988). Anatomy of the ankle and foot. *Physica Therapy*, 63(12), 1802-14.

Ringleb, S., Kavros, S., Kotajarvi, B., Hansen, D., Kitaoka, H., and Kaufman, K. (2007). Changes in gait associated with acute stage II posterior tibial tendon dysfunction. *Gait and Posture*, 25, 555-64.

Robbins, S.E. and Hanna, A.M. (1987). Running-related injury prevention through barefoot adaptation. *Medicine and Science in Sports and Exercise*, 19(2), 148-156.

Rosager, S., Aagaard, P., Dyhre-Poulsen, P., Neergaard, K., Kjaer, M., and Magnusson, S.P. (2002). Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scandinavian Journal of Medicine and Science in Sports*, 12(2), 90-98.

Salathe, E.P. and Arangio, G.A. (2002). A biomechanical model of the foot: The role of muscles, tendons, and ligaments. *Journal of Biomedical Engineering*, 124, 281-87.

Saltzman, C., Nawoczenski, D., and Talbot, K. (1995). Measurement of the medial longitudinal arch. *Archives of Physical Medicine and Rehabilitation*, 76, 45-49.

Schlee, G., Milani, T., and Roemer, K. (2009). Plantar pressure distribution, rearfoot motion and ground reaction force after long distance running. *Footwear Science*, 1(3), 129-134.

Sell, K.E., Verity, T.M., Worrell, T.W., Pease, B.J., and Wigglesworth, J. (1994). Two measurement techniques for assessing subtalar joint position: a reliability study. *Journal of Orthopaedic and Sports Physical Therapy*, 19(3), 162-7.

Semple, R., Murley, G., Woodburn, J., and Turner, D. (2009). Tibialis posterior in health and disease: a review of structure and function with specific reference to electromyographic studies. *Journal of Foot and Ankle Research*, 2, 24.

Sharkey, N.A., Ferris, L., Smith, T.S., and Matthews, D.K. (1995). Strain and loading of the second metatarsal during heel-lift. *Journal of Bone and Joint Surgery (American)*, 77(7), 1050-7.

Sharkey, N.A., Donahue, S.W., and Ferris, L. (1999). Biomechanical consequences of plantar fascial release or rupture during gait. Part II: Alterations in forefoot loading. *Foot and Ankle International*, 20(2), 86-96.

Simkin, A., Leichter, I., Giladi, M., Stein, M., and Milgrom, C. (1989). Combined effect of foot arch structure and an orthotic device on stress fractures. *Foot and Ankle*, 10(1), 25-9.

Snook, A.G. (2001). The relationship between excessive pronation as measured by navicular drop and isokinetic strength of the ankle musculature. *Foot and Ankle International*, 22(3), 234-40.

Song, J., Hillstrom, H.J., Secord, D., and Levitt, J. (1996). Foot type biomechanics comparison of planus and rectus foot types. *Journal of the American Podiatric Medical Association*, 86(1), 16-23.

Stacoff, A., Nigg, B., Reinschmidt, C., van den Bogert, A.J., and Lundberg, A. (2000). Tiobioalcalneal kinematics of barefoot versus shod running. *Journal of Biomechanics*, 33, 1387-95.

Stolwijk, N.M., Duysens, J., Louwerens, J.W.K., and Keijsers, N.L.W. (2010). Plantar pressure changes after long distance walking. *Medicine and Science in Sports and Exercise*, DOI: 10.1249/MSS.0b013e3181e305f4.

Subotnick, S.I. (1985). The biomechanics of running: Implications for the prevention of foot injuries. *Sports Medicine*, 2, 144-153.

Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., and Lloyd-Smith, R. (2002a). Plantar fasciitis: A retrospective analysis of 267 cases. *Physical Therapy in Sports*, 3, 57-65.

Taunton, J.E., Ryan, M.B., Clement, D.B., McKenzie, D.C., Lloyd-Smith, D.R., and Zumbo, B.D. (2002b). A retrospective case-control analysis of 2002 running injuries. *British Journal of Sports Medicine*, 36, 95-101.

Thordarson, D.B., Hedman, T., Lundquist D., and Reisch, R. (1998). Effect of calcaneal osteotomy and plantar fasciotomy on arch configuration in a flatfoot model. *Foot and Ankle International*, 19(6), 374-8.

Tranberg, R. and Karlsson, D. (1998). The relative skin movement of the foot: A 2-D roentgen photogrammetry study. *Clinical Biomechanics*, 13, 71-6.

van Gent, R.N., Siem, D., van Middelkoop, M., van Os, A.G., Bierma-Zeinstra, S.M.A., Koes, B.W., et al. (2007). Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *British Journal of Sports Medicine*, 41(8), 469-80.

Vaughan, C.L., Davis, B.L., and O'Connors, J.C. (1992). *Dynamics of Human Gait*. Human Kinetics, Champaign, IL.

Vinicombe, A., Raspovic, A., and Menz, H. (2001). Reliability of navicular displacement measurement as a clinical indicator of foot posture. *Journal of the American Podiatric Medicine Association*, 91, 262-8.

Voigt, M., Bojsen-Moller, F., Simonsen, E.B., and Dyhre-Poulsen, P. (1995). The influence of tendon Young's modulus, dimensions and instantaneous moment arms on the efficiency of human movement. *Journal of Biomechanics*, 28, 281-291.

Walker, M. and Fan, H.J., (1998). Relationship between foot pressure pattern and foot type, *Foot and Ankle International*, 19, 379-383.

Ward, E.D., Smith, K.M., Cocheba, J.R., Patterson, P.E., and Phillips, R.D. (2003). In vivo forces in the plantar fascia during the stance phase of gait. Sequential release of the plantar fascia. *Journal of the American Podiatric Medical Association*, 93(6), 429-442.

Wearing, S., Smeathers J., Yates, B., Sullivan, P., Urry, S., and Dubois, P. (2004). Sagittal movement of the medial longitudinal arch is unchanged in plantar fasciitis. *Medicine and Science in Sports and Exercise*, 36(10), 1761-7.

Wearing, S.C., Urry, S., Perlman, P., Dubois, P., and Smeathers, J. (1999). Serial measurement of calcaneal pitch during midstance. *Journal of the American Podiatric Medical Association*, 89(4), 188-93.

Wearing, S.C., Urry, S., Perlman, P., Smeathers, J., and Dubois, P. (1998). Sagittal plane motion of the human arch during gait: A videofluoroscopic analysis. *Foot and Ankle International*, 19(11), 738-42.

Weist, R., Eils, E., and Rosenbaum, D. (2004). The influence of muscle fatigue on electromyogram and plantar pressure patterns as an explanation for the incidence of metatarsal stress fractures. *American Journal of Sports Medicine*, 32(8), 1893-98.

Whiting, W. and Zernicke, R. (2008). *Biomechanics of musculoskeletal injury* (2nd ed.). United States of America: Human Kinetics, p. 90.

Whiting, W.C. and Zernicke, R.F. (1998). *Biomechanics of Musculoskeletal Injury*. Champaign, IL: Human Kinetics, p.119.

Williams, D., McClay, I., and Hamill, J. (2001). Arch structure and injury patterns in runners. *Clinical Biomechanics*, 16, 341-7.

Williams, D.S. and McClay, I.S. (2000). Measurements used to characterize the foot and the medial longitudinal arch: Reliability and validity. *Physical Therapy*, 80(9), 864-71.

Williams, D.S., McClay Davis, I., Scholz, J.P., Hamill, J., and Buchanan, T.S. (2004). High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait and Posture*, 19(3), 263-269.

Wolf, P., Stacoff, A., Liu, A., Nester, C., Arndt, A., Lundberg, A., and Stuessi, E. (2008). Functional units of the human foot. *Gait and Posture*, 28, 434-441.

Wu, W.L., Chang, J.J., Wu, J.H., Guo, L.Y., and Lin, H.T. (2007). EMG and plantar pressure patterns after prolonged running. *Biomedical Engineering: Applications, Basis and Communications*, 19(6), 383-388.

Xiong, S., Goonetilleke, R.S., Witana, C.P., Weerasinghe, T.W., and Au, E.Y.L. (2010). Foot Arch Characterization. A Review, a New Metric, and a Comparison. *Journal of the American Podiatric Medical Association*, 100(1), 14-24.

Yang, S.M., Kayano, J., Norimatsu, T. Fujita, M., Matsusaka, N., and Suzuki, R. (1985). Dynamic changes of the arches of the foot during walking, in: *Biomechanics IX-A*, Winter, D.A., Norman, R.W., Wells, R.P., Hayes, K.C., and Patla, A.E. (Eds.). Champaign, IL: Human Kinetics Publishers, pp. 417-422.

Yoshikawa, T., Mori, S., Santiesteban, A.J., Sun, T.C., Hafstad, E., Chen, J., and Burr, D.B. (1994). The effects of muscle fatigue on bone strain. *Journal of Experimental Biology*, 188, 217-233.

Zelik, K.E. and Kuo, A.D. (2010). Moving and shaking: Soft tissue work in human walking. *Proceedings of the American Society of Biomechanics 34th Annual Meeting*.

Zifchock, R.A., Davis, I., Hillstrom, H., and Song, J. (2006). The effect of gender, age, and lateral dominance on arch height and arch stiffness. *Foot and Ankle International*, 27(5), 367-72.

APPENDIX A. EXTENDED LIMITATIONS

Interpretation of the results must be considered with the limitations of the study. One of the main limitations was the removal and replacement of reflective markers. The magnitude of arch collapse is very small, so inexact marker placement after the run may explain the lack of change. Secondly, the author is not a clinician and experienced at locating certain bony landmarks (specifically the navicular). This and the custom-made foot measurement system likely resulted in the lower reliability between days. Skin artifact can be of the same magnitude as the changes observed (Maslen and Ackland, 1994; Tranberg and Karlsson, 1998). For example, the navicular marker moved 3.4 mm more in the plantar direction when going from static neutral to 5° everted (Maslen and Ackland, 1994). This, however, seems counterintuitive considering the skin on the medial side becomes more taut during eversion as the underlying bones rotate inferiorly. We are reassured that MLA collapse does occur during gait based on fluoroscopy and bone-pin studies (Arndt et al., 2007; Gefen, 2003; Wearing et al., 1998; Wearing et al., 1999; Wolf et al., 2008). Nonetheless, some of our variables may be invalid due to the inherent error of skin movement. Participants ran the 45 minutes shod but tested barefoot, which may under- or overestimate arch deformation during the actual run. Eversion excursion may remain the same or decrease in barefoot running compared to shod (Eslami et al., 2007; Stacoff et al., 1991), and since eversion is related to change in navicular height (Mathieson et al., 2004), the actual amount of MLA collapse in shod running and walking may be underestimated by the current study. On the other hand, there is no difference in plantarflexion moments between shod and barefoot running (Kerrigan et al., 2009), and if MLA collapse is partially caused by triceps surae contraction, we would not anticipate MLA deformation to be

different when shod. Contrarily, MLA deformation may be greater when running barefoot, because somatosensory input indicates a more rigid surface and adapts by becoming more compliant (Robbins and Hanna, 1987). Finally, we did not monitor equal loading of the feet when applying markers, but healthy adults are usually within 4% body weight or less (Tessem et al., 2007).

APPENDIX B. EXTENDED RESULTS

Table 3
Kinematic variables for walking—Mean (SD)

	Navicular displacement (mm)	Arch lengthening (mm)	Change in AHI	Time to peak ND (% stance)	Time to peak AL (% stance)	Time to peak change AHI (% stance)
Pre-Run						
Men	4.9 (2.1)	4.3 (1.5)	0.0218 (0.007)	75 (10)	26 (7)	65 (26)
Women	4.5 (1.4)	4.3 (1.6)	0.0251 (0.011)	75 (6)	33 (11)	59 (24)
Post-Run						
Men	5.2 (2.5)	4.8 (1.9)	0.0242 (0.008)	78 (6)	25 (9)	65 (25)
Women	4.2 (1.5)	4.0 (1.2)	0.0224 (0.007)	76 (4)	30 (13)	58 (23)

AHI=arch height index; ND=navicular displacement; AL=arch lengthening

Table 4
Kinematic variables for running—Mean (SD)

	Navicular displacement (mm)	Arch lengthening (mm)	Change in AHI	Time to peak ND (% stance)	Time to peak AL (% stance)	Time to peak change AHI (% stance)
Pre-Run						
Men	7.4 (2.3)	6.0 (1.7)	0.0258 (0.006)	54 (7)	44 (12)	37 (16)
Women	6.8 (2.2)	5.9 (2.3)	0.0302 (0.011)	56 (6)	36 (9)	50 (16)
Post-Run						
Men	7.5 (2.9)	6.4 (2.2)	0.0288 (0.009)	55 (5)	42 (13)	38 (19)
Women	6.6 (2.2)	5.3 (1.7)	0.0283 (0.009)	55 (5)	36 (8)	44 (15)

AHI=arch height index; ND=navicular displacement; AL=arch lengthening

Table 5
Arch stiffness variables—Mean (SD)

	Collapse arch stiffness (N/mm)*	Reformation arch stiffness (N/mm)*	Arch rigidity index
Pre-Run			
Men	155 (80)	228 (61)	0.953 (0.020)
Women	128 (31)	181 (72)	0.945 (0.022)
Post-Run			
Men	152 (80)	229 (59)	0.944 (0.019)
Women	134 (43)	190 (73)	0.958 (0.018)

*Calculated for running only

ACKNOWLEDGEMENTS

Thank you Dr. Derrick for all your guidance and patience throughout my thesis and all the other projects we worked on together. I am so glad I transferred to Iowa State and switched from pre-graphic design to kinesiology and volunteered for a running study, which first exposed me to research. I could not have asked for a better advisor with similar running-related interests. Thank you for being willing to explore the complexity of the foot. What I appreciate the most, though, is being treated like an equal and being comfortable talking with you and asking questions. *None* of this would have been possible without your help.

I would also like to thank Erin Ward for all his clinical foot advice and help with my thesis and other presentations. Research is great but it is the clinical application that is most important. I learned so much by the foot dissection and am further intrigued by the complexity of the foot.

Thanks to everyone else who helped me with the development of the idea (Dr. Derrick, Erin Ward, Stacey Meardon), pilot work (Dr. Derrick, Eric Sterner, Danielle Barkema), data collections (Dr. Derrick, Eric Sterner, Brandon Rooney, Michelle Hall), statistics (Dr. Derrick, Michelle Hall, Dr. Martin), and revisions (Eric Sterner, Michelle Hall, Dr. Smiley-Oyen, and my POS committee). I would especially like to thank Michelle for being an *amazing* friend willing to listen to me complain and step through this whole process together. Finally, thank you to my parents for believing in me and letting me decide what I wanted to do with my life, and my fiancé, Matt, who put up with me during the stressful times and offered words of encouragement.