2019

Barefoot Training: Effects on EMG Activity of Gluteus Medius and Tensor Fascia Latae in Habitually Shod Runners

Tom Linner
University of North Dakota

Casey Murphy
University of North Dakota

Jeremy O'Keefe
University of North Dakota

BAREFOOT TRAINING: EFFECTS ON EMG ACTIVITY OF GLUTEUS MEDIUS AND TENSOR FASCIA LATAE IN HABITUALLY SHOD RUNNERS

By

Tom Linner, SPT
Bachelor of Science in Biology
University of Wisconsin - La Crosse

Casey Murphy, SPT
Bachelor of Science in Health Studies
University of North Dakota

Jeremy O'Keefe, SPT, CSCS
Bachelor of Science in Health Studies
University of North Dakota

A Scholarly Project Submitted to the Graduate Faculty of the

Department of Physical Therapy

School of Medicine and Health Sciences

University of North Dakota

In partial fulfillment of the requirements for the degree of

Doctor of Physical Therapy
Grand Forks, North Dakota
May, 2019

This Scholarly Project, submitted by Jeremy O'Keefe, Tom Linner, and Casey Murphy in partial fulfillment of the requirements for the Degree of Doctor of Physical Therapy from the University of North Dakota, has been the reviewed by the Advisor and Chairperson of Physical Therapy under whom the work has been done and is hereby approved.

Gary Schindler, PT, PhD, OCS, SCS, LATC, CSCS

David Relling, PT, PhD, Department Chair

PERMISSION

Title: Barefoot Training: Effects on EMG Activity of Gluteus Medius and Tensor Fascia Latae in Habitually Shod Runners.

Department: Physical Therapy

Degree: Doctor of Physical Therapy

In presenting this Scholarly Project in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the Department of Physical Therapy shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my work or, in his absence, by the chairperson of the department. It is understood that any copying or publication or other use of this Scholarly Project or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and the University of North Dakota in any scholarly use which may be made of any material in this scholarly project.

Signature: ______________

Signature: Casey Murphy

Signature: ______________

Date: 10/17/18

TABLE OF CONTENTS

Acknowledgments

The authors of this paper would like to thank our advisor Gary Schindler for his dedication and commitment to excellence. Gary continually offered time and expertise to educate and guide our group through this project. We would also like to thank Department Chair, Dave Relling. Dave worked continuously to ensure that we were allowed the resources we needed, in addition to supplying his knowledge and expertise to this project. This project was made possible by the contributions and support of these two professors.

LIST OF FIGURES

LIST OF TABLES

Abstract

Purpose/Hypothesis: Running has been a common practice in humans since the species' dawn. Due to its relative ease and low cost, running continues to be one of the most popular forms of exercise today. Although running provides many benefits such as disease prevention, injury prevalence in running is high. The trend of minimalist shoes and barefoot training has gained popularity over the decade as a return to a more natural form of running. Some researcher hypothesize that barefoot running can reduce injury rate by changing the biomechanics of the runner. In this study we propose a different hypothesis: barefoot running changes activity of musculature of the hip, increasing activation in muscles that are commonly weak in injured runners. Research investigating the hip muscle activity and movement with barefoot running is lacking in literature; thus, giving rise to the purpose of this study. This multifactorial study was performed to explore the effect of barefoot training on the muscular activity of the gluteus medius (GM) and tensor fascia latae (TFL). The hypothesis being tested was that barefoot training period would increase the muscle activity of GM and decrease the muscle activity of TFL.

Materials/Methods: Twenty-two subjects, 14 females and 8 males, with a mean age of 22.8 completed the pre-testing electromyography (EMG) analyses. EMG muscle activity of TFL and GM was recorded during a maximal isometric contraction, a barefoot running and walking trial and a shod running and walking trial. Subjects were randomly assigned to a barefoot running group (N=13) and shod running group (N=9). Participants completed a 6-week training program consisting of running twice a week. The first week of training consisted of 10 minutes of running (either barefoot or shod) with a 2- minute increase each week, reaching a maximum running period of 20 minutes during the final week. Following the training program, post-test EMG was performed and analyzed.

Results: No significant differences in change of EMG activity of the GM and TFL was found between the barefoot and shod training groups from pre-testing to post-testing data collection.

Conclusions: Due to no statistically significant differences in change of EMG activity of the GM and TFL between the training groups from pre- to post-test trials, further research is recommended to explore the impact of a barefoot training protocol on GM and TFL muscle activity.

Clinical Relevance: This study provides insight to the muscle activity occurring at the hip when foot attire is altered during training. No statistically significant change was found between barefoot or shod training groups in regard to change in muscle activity from pre-test to post-test. This lack of statistical significance may have been due to lack of statistical power, as the number of subjects was low. The training period also may have not provided enough volume to create a stimulus to significantly change muscle activity. While there were no statistically significant findings, trends in the data pointed towards a greater change in GM activity for the barefoot group from pre-test to post-test. Replicating the study with a higher number of subjects or a larger training volume may yield significant results in future

research. In addition, collecting other data such as V02 max, running economy or foot strike pattern also may reveal other physiological changes that can occur with barefoot training.

Chapter I

Introduction

Endurance running has been inherent to the human experience from the species' dawn. Many anthropologists and scientists hypothesize that early Hominins used their endurance running prowess to pursue their prey, chasing animals until they were to collapse in exhaustion.[1,2] Olympians to hobby joggers today, all benefit from the evolutionary adaptations that have taken place to make *Homo sapiens* an efficient endurance running machine. As running and jogging participation increases in America, with 35.5 million participants in 2010, so does the incidence of injury.[3] There is some variability in injury rate of runners across studies, but all indicate that injuries in the running population are relatively common. A systematic review published in the British Medical Journal analyzed 17 studies and found the overall incidence of reported lower extremity injuries was as high as 79%. The most commonly injured joint was the knee, with an injury rate of 7.2-50%.[4] A meta-analysis published in the Journal of Sports Medicine, reported that the injury rate per 1000 hours of running was 17.8 for novice runners and 7.7 for recreational runners.[5] This statistic would indicate that if a novice runner ran 30 minutes a day for a year they would incur, on average, over three injuries during that time. The current trend of minimalist shoes is a response to this common occurrence of injury, as runners seek to utilize the natural anatomy of the foot instead of the foam and plastic found in the conventional running shoe.

Minimalist footwear was defined by a group of forty-two experts, mainly consisting of scientists and researchers, as “footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and absence of motion control and stability devices.”[6] Minimalist footwear can have an effect of the way a runner makes initial contact with the ground while running. Foot strike patterns are commonly divided into three different categories, the hindfoot or rearfoot (talus and calcaneus), midfoot (navicular, cuboid and cuneiforms) and forefoot (metatarsals and phalanges).[7] The features of a minimalist shoe allow the runner to utilize a forefoot strike more easily, as runners wearing conventional running shoes commonly perform a rearfoot strike pattern.[8]

Many studies have found that habitually shod runners with rearfoot strikes transition to a forefoot/midfoot strike when running barefoot.[9,10,11,12] When running with a forefoot/midfoot strike pattern, the body absorbs the ground reaction forces with eccentric control after initial contact.[13] One study also found a reduction in peak impact magnitudes of ground reaction forces in shod rearfoot strikers when switching to barefoot running.[14] These biomechanical variations associated with a forefoot strike may also affect injury rate. A study involving 52 collegiate runners found the rate of repetitive stress injuries to be twice as high in the athletes with a rearfoot strike than a forefoot strike.[15] The authors hypothesize that one of the primary reasons for the relationship between strike pattern and injury rates is the reduction of peak ground reaction force when utilizing forefoot strike rather than rearfoot strike. However, what if there were other mechanisms, relating to muscle activity, which could account for this reduction in injury rate?

Due to a smaller base of support, greater kinematic changes must be made proximally up the chain to stabilize the body against gravity when the foot strikes the ground with the forefoot rather than rearfoot. For example, the gluteus medius acts as a stabilizer at foot strike, preventing the knee from moving into genu valgum.[16] A study involving thirty runners with overuse injuries and thirty runners without injuries, revealed that hip abductor and hip flexors were significantly weaker in the injured group in comparison to the non-injured control group.[17] Not only do hip abductors such as gluteus medius act to prevent ipsilateral genu valgum, they also help stabilize the pelvis to reduce contralateral pelvic drop.[8] Gluteus medius is a key muscle in stabilization of the lower extremity during gait. If the lower extremities can become more stable during gait, a more biomechanically desirable stride will be found. As the gait becomes more biomechanically efficient, it will allow for ideal joint kinematics and a corresponding reduction in injury rate.

Injuries to endurance runners will never be eliminated, however there is room for improvement regarding injury rate with hip abductor weakness possibly predisposing individuals to injury. If utilizing an altered foot strike during barefoot training corresponds with an increased activity of hip abductors, it would be a useful rehabilitation method. Runners would be able to reduce their risk of injury, while performing their main objective: running. The purpose of the study is to explore the effects of a barefoot training protocol on the EMG activity of the gluteus medius and TFL, along with assessment of lateral pelvic drop, on habitually shod runners.

Chapter II

Literature Review

Biomechanics

Running shoes have evolved and progressed over the last century. Shoes formerly consisted of a flat sole with a leather top. Now, they often consist of an elevated heel, arch support, and various levels of heel cushioning. These changes to footwear have been shown to change the way humans run when compared to barefoot running. Foot-strike, cadence, joint movements, ground reaction forces, joint forces and proprioceptive input are a few of the factors that are different when comparing the biomechanics of running in modern day footwear to barefoot running.[18]

Kinematics

Strike patterns during the shod running cycle can be classified under two main categories and a third, less common, category: Rear-foot strike (RFS), Mid-foot strike (MFS), and Fore-foot strike (FFS). During shod running: 75% of runners exhibit a RFS pattern, 20% a MFS, and 5% a FFS.[19] Changing between shod and barefoot running can have a variety of kinematic changes on the body. FFS and MFS runners have been shown to decrease their stride length when switching to barefoot from shod running. In comparison, rear-foot strikers also decreased stride length, in addition to demonstrating a plantarflexed foot position at contact when changing to barefoot running.[20] These changes are best seen when comparing stride length and cadence. Stride length and cadence are closely associated. Therefore, cadence increases with immediate transition from shod running to barefoot running with relation to decreased stride length.

Hip kinematics are affected when shod runners switch to barefoot running. Decreased hip adduction, hip internal rotation, and contralateral pelvic drop was shown with immediate change to barefoot running.[21] Biomechanical changes potentially during stance and push-off phases have also been identified to contribute to increased instability.[21,22] While these studies identified immediate changes. There exists a need to identify the effect barefoot training has on running kinematics

Kinetics

A difference in ground reaction force has been identified between shod and barefoot running. Shod running is associated with increased ground reaction force and peak magnitude when compared with barefoot running.[23] In addition to decreased ground reaction forces, patellofemoral joint stress and patellofemoral joint reaction forces were measured to decrease by 12% when shod running was compared to barefoot running.[24] A similar result was found in a 2014 study that identified significantly reduced patellofemoral contact force in barefoot running compared to shod. However, they did note that Achilles tendon loading significantly increased in barefoot running.[25] The achilles tendon may be acting as a “shock absorber” individuals run with a FFS. This could explain the decreased patellofemoral and ground reaction forces that coincide with increased achilles tendon loading.

Gluteus Medius Function

In 2013, over 50 million Americans participated in running or jogging, a rise of 5% since the previous year. Although the benefits of physical activity are well documented, musculoskeletal injuries are common in runners of all levels.[26] Electromyography (EMG) studies have often been used to assess muscle function during the running and gait cycle in habitual shod runners. In a study of 30 healthy patients, peak forces produced by the gluteus medius during running was substantially greater than several other hip muscles, which included biceps femoris, semimembranosus, semitendinosus, gluteus maximus, gluteus minimus, TFL, rectus femoris, sartorius, psoas, illiacus, adductor magnus, adductor brevis, adductor longus, and piriformis.[27] In addition, a review performed by Semciw[26] determined a burst of glutes medius monophasic EMG activity during the loading phase in the first 5-10% of the gait cycle. However, there was limited evidence from individual studies that running speed, cadence, and gender affect GM EMG function in healthy runners.

Barefoot running has become more popular. With increasing popularity studies have begun to compare the relationship of injuries, biomechanics and hip muscle activity in barefoot and shod runners. Tam et al[28], found in 26 individuals completing an 8-week progressive barefoot running program, posterior hip activity (gluteus medius and biceps femoris) increased in pre-activity which may indicate a muscle tuning response that increases muscle tension and stabilization for both knee and hip joints during ground contact. Thus, attenuating the initial loading rate by preparing the joint during swing and tuning the muscle for ground contact.[28]

Gluteus Medius and Injury

Patellofemoral Pain Syndrome

Patellofemoral pain is an idiopathic condition characterized by aching pain in the peripatellar area, which can be exacerbated by physical activity, including running. Patellofemoral pain is the most common musculoskeletal overuse injury in physically active individuals regardless of sex or age.[29] Patellofemoral pain continues to be an issue in competitive and recreational athletes. Possible treatment for patellofemoral pain syndrome was explored by Bonacci et al[30], in 22 trained runners utilizing both neutral running shoes and barefoot training. Running barefoot decreased peak patellofemoral joint stress by 12% in comparison to shod running.[30] Barton et al[31] found, moderate to strong evidence indicates gluteus medius muscle activity is delayed and shorter during both functional stair activities, as well as running in individuals with patellofemoral pain syndrome. Therefore, increasing in gluteus medius and tensor fascia latae activity to better control femur and pelvic motion may be significant factors during the rehabilitation and prevention of patellofemoral pain.

Low Back Pain

The prevalence of chronic low back pain among recreational runners has been reported as high as 13.6% in the United States.[32] In a study estimating the Global Burden of Disease, low back pain ranked highest in terms of years lived with disability and sixth in overall burden.[33] These numbers are alarming and have led to recent research to address interventions for running patients suffering from low back impairments.

Treating low back pain can be difficult to address in runners. Cai et al[34] examined recreational runners and found those who participated in lower limb exercises, including hip and knee strengthening, had greater improvement in self-rated running capability, knee extension strength, greater increase in running step length, and similar reduction in running induced pain and improvement in back muscle function in comparison to lumbar extension and lumbar stabilization exercises. A four-week study investigated a change in lumbar positioning of 17 participants who transitioned from habitually shod running (10-50 km/week) to barefoot running. Significant differences were found in mean lumbar posture during stance phase with increased lumbar extension when transitioning to barefoot running. Furthermore, a significant reduction in muscle activity of the contralateral lumbar paraspinals was recorded. This observed reduction in contralateral muscle activation in a more upright position may lead to reduction in impact shock after training.[35] Although adequate activation during running is needed to support the spine and create coordination between the trunk and pelvis, excessive lumbar paraspinal activity may be a sign of dysfunction. Van der Hulst et al[36] examined patients with chronic low back pain in which he found increased lumbar muscle activity during all periods of stride, suggesting difficulties with total muscle relaxation.[35,36] These discoveries could lead to a continued change in thinking for rehabilitation of patients suffering from low back pain to a minimalist or barefoot running protocol.

Achilles Tendinopathy

Achilles tendinopathy is a term used by a combination of pain, swelling, and impaired performance of the achilles tendon.[18] Individuals with achilles tendinopathy have been shown to have changes in ankle and hip motions. These motions include increased ankle eversion, time to maximum pronation, calcaneal pronation, calcaneal inversion, and decreased hip flexion in the pre-swing phase of gait. Individuals with achilles tendinopathy were reported to have reductions in gluteus medius onset and activity.[37] Further verification of these results could play vital roles in prevention and rehabilitation in runners, recreational and competitive, suffering from achilles tendinopathy.

Osteoarthritis

Osteoarthritis (OA) is the most common form of arthritis, involving inflammation and structural changes of the joint, causing pain and functional disability for many. In a systematic review measuring the global burden of 291 conditions, hip and knee osteoarthritis was ranked 11th highest in global disability.[38] Evidence-based clinical guidelines identified by Cibulka et al, state hip abduction strength (specifically gluteus medius) and motor control are physical impairments which need to be addressed with treatment in patients with the presence of hip osteoarthritis.[39] The gluteus medius has been linked as a factor in patients with hip osteoarthritis. Continued function in the presence of neuromuscular alterations may hasten the progression of joint disease and result alternate patterns in functional movements. Furthermore, Dwyer et al,[40] explored muscle activity of the gluteus medius in patients completing functional activities with unilateral, end-stage osteoarthritis of the hip joint scheduled for a total joint replacement compared to healthy individuals. Dwyer et al[40] found increased sEMG activity in patients with end-stage OA compared to healthy patients. This increase in sEMG activity may be a compensatory response to muscle weakness. Patients with insufficient GM strength may require increased central nervous system input to the muscle to maintain proper pelvic position in stance, thus resulting in higher sEMG activity.[41] In conclusion, interventions including strengthening exercises which target the gluteal muscles should assist in neuromuscular control and result in improved muscular strength.

Surface Electromyography (sEMG)

Surface Electromyography (sEMG) is used extensively to measure the electrical activity within skeletal muscles in clinical and research applications. These applications include; investigating neurological diseases, assessment of motor control and muscle dysfunction and the evaluation of rehabilitation/exercise interventions.[42] Normalizing to a reference signal is essential when analyzing and comparing sEMG signals across individuals or trials.[43] While capturing data through sEMG, it is imperative to realize the electrical activity identified is from the examined muscle rather than a representation of strength or muscle force. SEMG recordings provide a safe, easy, and noninvasive method that allows objective quantification of the energy of the muscle. In a study conducted by Bussey et al, day to day reliability was deemed to have a high (.7-.89) to very high (>.90) Intraclass Correlation Coefficient for gluteus medius and biceps femoris muscles when measuring maximum voluntary contraction and sub-maximal volumetric contraction, .84-.98 and .73-.95, respectively.[44] Experience between examiners plays a role in intra and inter-session reliability in placement and execution of pre-recording procedures. The muscles under consideration in this study via sEMG will be gluteus medius and tensor fascia latae. Due to interference, which may lead to unreliable data, this study will be conducted utilizing wireless EMG to increase reliability and allow subjects to normalize their running style. SEMG reliability and validity for gluteus medius or tensor fascia latae during shod or barefoot running was not considered in this literature.

Tensor Fascia Latae and Iliotibial Tract

The tensor fascia latae (TFL) muscles lies along the lateral portion of the iliac crest. Hip flexion, abduction, and medial rotation are the three actions performed by the TFL. It inserts into the iliotibial band (ITB), a fascial structure running from the hip to the knee. The ITB has been scrutinized as a potential source of pain and injury in runners. IT band friction syndrome is often attributed to lateral knee pain in runners. A recent study identified the IT band as a source of elastic energy storage during running. The IT band can store roughly 1 J of energy during jogging and 7 J of energy during fast running.[45] The TFL has a direct influence on this energy transfer due to its insertion into the IT band. Perhaps altered mechanics of barefoot running and TFL activation could contribute to decreased incidence of ITB friction syndrome.

Chapter III

Methods

Outlined below are the methods used throughout the study. These include patient selection criteria, training period structure, and EMG data collection.

Participant Selection

Participants were recruited via an in-class presentation outlining the study. Study details were shared with the University of North Dakota first- and second-year physical therapy students. Inclusion criteria and study information was distributed through email communication. To participate individuals must be (1) a rearfoot striker, (2) currently complete between 0-20 miles of running per week, (3) age 20-30 (4) habitually shod runner. Those with (1) a significant injury to the lower extremity in the past 6 months, (2) use of NSAIDS, (3) cardiopulmonary pathologies or significant medical history, or (4) forefoot strikers were excluded.

Protocol

Prior to training, baseline testing was conducted to determine EMG activity of the gluteus medius and tensor fascia latae during Maximum Voluntary Contraction (MVC), as well as barefoot and shod walking and running. Participants ran two days per week for a six-week training period. The training sessions took place on the University of North Dakota campus at the High-Performance Center. Subjects began with a 3-minute warm up walk around a 100-yard turf field followed by a dynamic warm-up (Figure 1). The running protocol began after all participants had completed the dynamic warm up. Participants began at a self-selected pace in a counterclockwise fashion for a predetermined amount of time then instructed to switch directions (clockwise) for another predetermined amount of time. Time amounts are detailed below (Table 1). Each training session concluded with a series of static stretches (Figure 2). Following the six-week training protocol, participants performed post-testing for EMG activity of the gluteus medius and tensor fascia latae as outline prior.

(A)

(B)

(C)

(D)

(E)

(F)

(G)

Figure 1 - Dynamic Warm Up Stretches:
(A) Lunge with a twist toward ceiling, (B) Knee to chest hug, (C) Lunge with a twist, (D,E) Hip Flexion/Extension leg swings, (F,G) Hip Abduction/Adduction leg swings

(A)

(B)

(C)

(D)

Figure 2 – Post Running Static Stretches: (A) Quadriceps, (B) Hamstring, (C) Piriformis, (D) Gastrocnemius

Table 1 - Running Outline: The table below demonstrates the amount of running time per direction throughout each week of training.

Week	Running Counterclockwise	Running Clockwise
Week #1	5 Minutes	5 Minutes
Week #2	6 Minutes	6 Minutes
Week #3	7 Minutes	7 Minutes
Week #4	8 Minutes	8 Minutes
Week #5	9 Minutes	9 Minutes
Week #6	10 Minutes	10 Minutes

EMG

Procedure

All participants completed an informed consent. Height and weight were measured, and BMI was calculated. Barefoot and shod trial order was randomly assigned to each subject to determine if the trial would begin with shoes off or shoes on. In the following section, electrode placement for the gluteus medius and tensor fascia latae will be described, in addition to MVC process and data collection.

Electrode Placement

Each electrode placement was prepared by berating the skin with sandpaper for a total of eight times. Each area was then cleansed with rubbing alcohol. Once electrodes were placed over each muscle, electrical impedance was measured using the NORAXON Electrode Impedance Meter. If the electrode impedance was greater than 10k, the electrode was removed, and the procedure was repeated. Foot contact sensors were applied to each of the participant's right foot. Sensors were placed on the first metatarsal head and the calcaneus, to identify timing of muscular activity with ground contact. This allows for clear distinction between stance and swing phases of the participants gait pattern. The leads were placed as follows (Figure 3):

- Lead One: Left Gluteus Medius
- Lead Two: Right Gluteus Medius
- Lead Three: Left Tensor Fascia Latae
- Lead Four: Right Tensor Fascia Latae

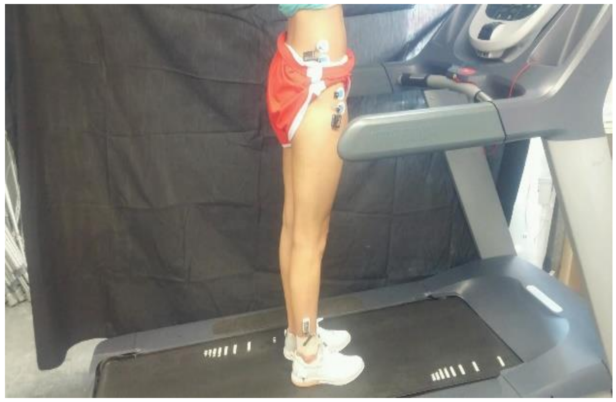
Gluteus Medius

The most cranial point of the greater trochanter and most cranial point of the iliac crest were identified through palpation and the distance between each point was measured in centimeters. A point was marked one-third the total distance beginning from the most cranial point of the iliac crest. The same process was completed on the contralateral side of the patient. The skin was prepared by berating the skin eight times with sandpaper then cleaned with rubbing alcohol. Two electrodes were placed so that the center of each electrode was two centimeters apart at each gluteus medius.[46]

Tensor Fascia Latae

The most caudal point of the anterior superior iliac spine was located by palpation technique and a mark was placed two centimeters distally. The skin was prepared with eight swipes of sandpaper followed by cleaning with rubbing alcohol. Two electrodes were placed over the mark, so the center of each electrode was two centimeters apart at each tensor fascia latae.[44] This process was completed bilaterally.

(A)



(B)

Figure 3 – Electrode Placement - (A) Shod, (B) Barefoot

Maximum Voluntary Contraction

Following electrode placement, participants completed bilateral gluteus medius and tensor fascia latae maximum voluntary contractions (MVC). To determine the participants MVC of the gluteus medius, participants were positioned side-lying, measurements completed with a goniometer were thirty degrees of hip abduction, neutral hip rotation, and zero degrees of hip flexion/extension (Figure 4). Two trials were performed in this position with one minute of rest between each trial. Testing of the MVC for the tensor fascia latae included the participant in side-lying, measurements completed with a goniometer were thirty degrees of abduction, neutral hip rotation, and forty-five degrees of hip flexion (Figure 5). Two trials were performed in this position with one minute of rest between each trial. Participants were asked to slowly lift their leg until contacting the belt and push maximally for five seconds. This process was repeated bilaterally for each muscle.

Figure 4 - Maximal Voluntary Contraction of Gluteus Medius: Subjects were positioned with thirty degrees of hip abduction, neutral hip rotation, and zero degrees of hip flexion/extension.

Figure 5 - Maximal Voluntary Contraction of Tensor Fascia Latae: Subjects were positioned with thirty degrees of hip abduction, neutral hip rotation, and forty-five degrees of hip flexion.

Data Collection

Data was collected while each participant walked on the treadmill at three-mph for 40 seconds then transitioned to running at six-mph for 40 seconds. The first 20 seconds of both the walking and running periods were used for the subjects to normalize their gait, while the final 20 seconds were used for recording EMG activity. The participants then donned or doffed their shoes depending on their random selection and repeated the walking and running trials.

Surface EMG electrodes were placed over the GM and TFL bilaterally through the method outlined in the above *Electrode Placement* section. EMG data was collected using an eight channel Noraxon Telemyo 2400 system. The EMG signals were rectified, smoothed (RMS 50) and then normalized to the respective maximal voluntary contraction prior to analysis.

Chapter IV

Results

Pre-testing EMG data was collected to establish baseline muscle activity for each of the 22 participants during barefoot walking, barefoot running, shod walking and shod running. Post testing EMG data was collected after the 6-week training period in which 13 participants ran barefoot, while 9 ran shod. This pre and post test data was examined using the Statistical Package for Social Sciences (SPSS). Each data comparison was analyzed utilizing an independent sample t-test to determine clinical significance.

Does barefoot training alter EMG activity in the tensor fascia latae?

Comparing training effect of barefoot versus shod running on the activation of the tensor fascia latae, no statistically significant results were noted. While no statistically significant results were found, there were general trends that could be clinically significant regarding muscle activation. TFL activity can be found depicted in Tables 2,3 and 6. Both groups saw and increase in TFL activity after the training period, although the shod training group saw a larger percent increase in EMG activity during all measured treadmill activities (Table 6). The largest difference was found in walking barefoot, as the barefoot group had a 29.67% increase in activity while the shod group had a 42.26% increase (12.59% difference).

Does barefoot training alter EMG activity in the gluteus medius?

There were no significant findings on the effect of barefoot running on EMG activity to the gluteus medius. However, there were consistent trends across all treadmill activities that suggests there could be clinical significance. The shod training group had a decrease in gluteus medius activity after the training period in all treadmill activities (Table 5). In contrast, the barefoot training group showed a decrease in activity during barefoot walking, but an increase in all other treadmill activity (Table 4). While the barefoot training group showed a decrease in EMG activity of GM during barefoot walking (-8.82%), the percent decrease was less than what was found in shod training group (-21.03%).

The largest differences when comparing training groups were observed during running activities. In regard to EMG activity during barefoot running, the barefoot training group increased 16.90%, while the shod training group had a decrease of 18.04%. Similarly, shod running EMG activity increased 12.36% for the barefoot training group and decreased 29.69% for the shod training group. When percent change is compared directly (Table 7), the barefoot training group demonstrated a more positive change in EMG activity of the gluteus medius during every treadmill activity. Possible causes of these trends in EMG activity are explored in the following discussion section.

Table 2. EMG Activity in TFL During Pre Testing and Post Testing

Barefoot Training Group

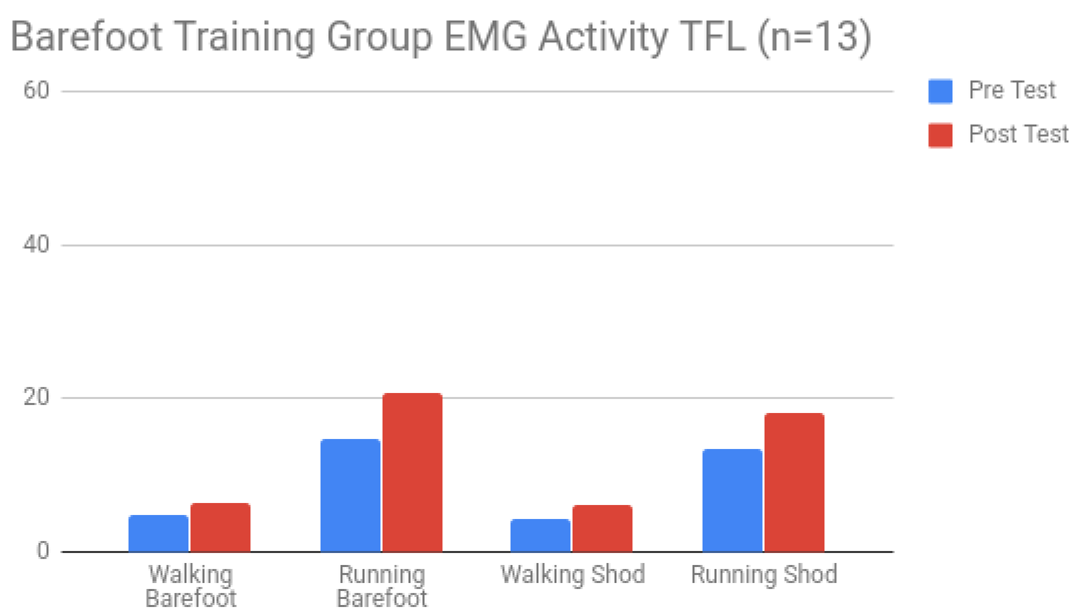


Table 3. EMG Activity in TFL During Pre Testing and Post Testing
Shod Training Group

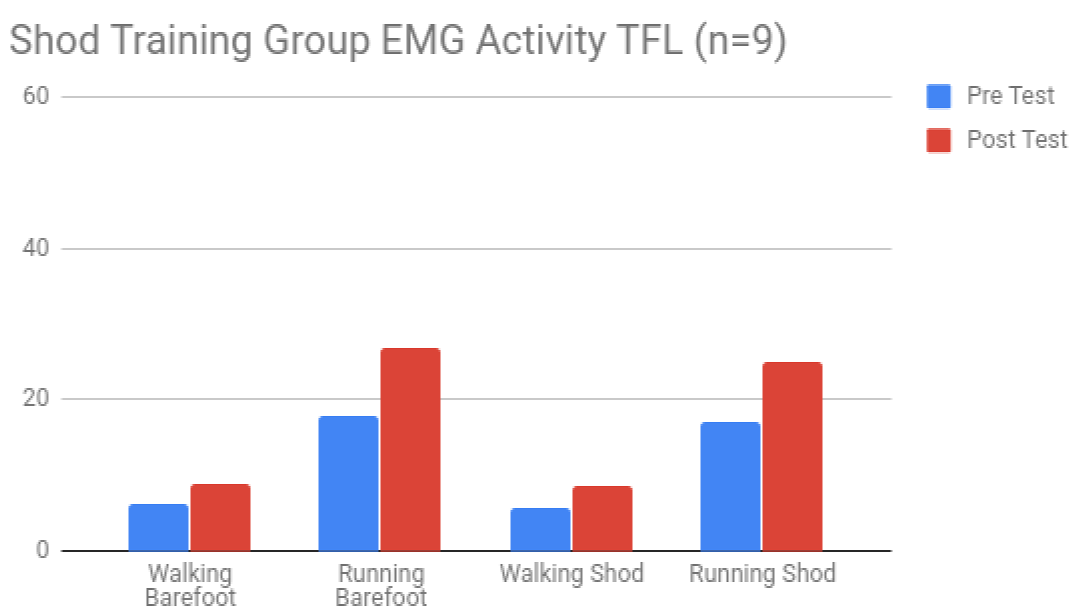


Table 4. EMG Activity in GM During Pre Testing and Post Testing

Barefoot Training Group

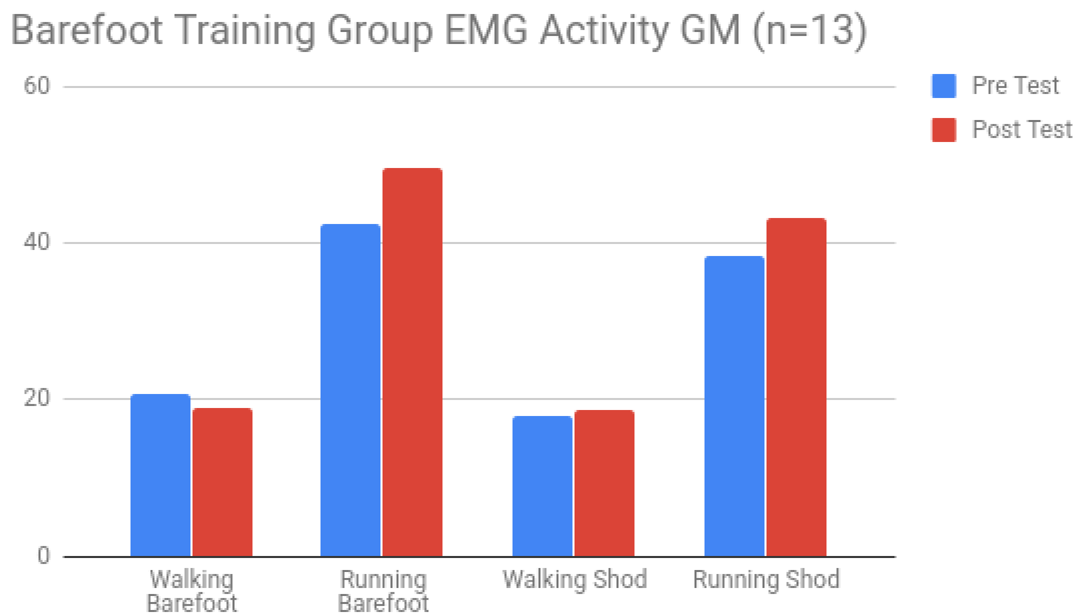


Table 5. EMG Activity in GM During Pre Testing and Post Testing
Shod Training Group

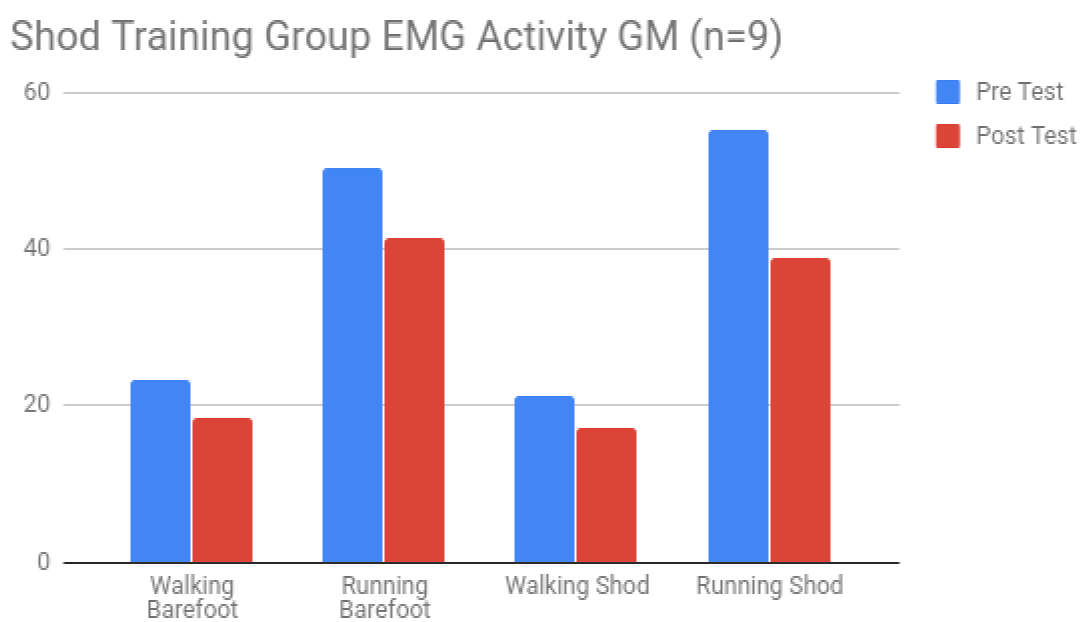


Table 6. Change in EMG Activity Between Pre Testing and Post Testing
TFL

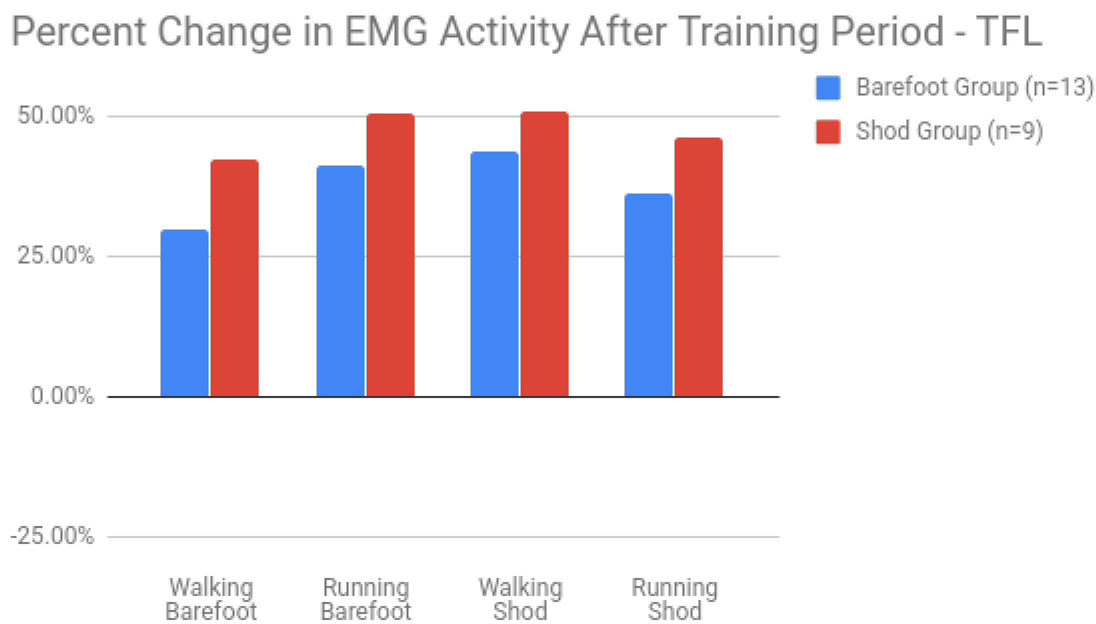
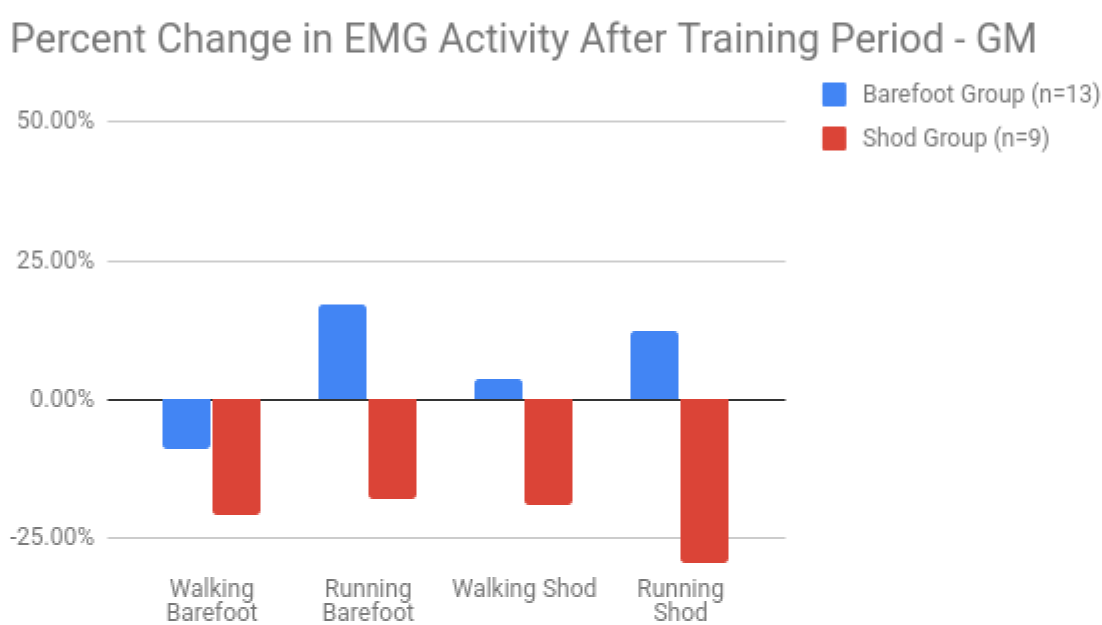


Table 7. Change in EMG Activity Between Pre Testing and Post Testing
GM



Chapter V

Discussion

Conclusion

This study investigated the training effect of barefoot running and EMG activation of gluteus medius and tensor fascia latae. We anticipated seeing an overall increase in activation of these hip muscles following barefoot training. Statistically, there was no significant difference between shod and barefoot groups regarding EMG activation of the gluteus medius and TFL muscles. However, we did find a non-statistically significant trend associated with the training program. The shod running group was found to have an overall decreased change in gluteus medius EMG activation and an increase in TFL EMG activation following the training period. The barefoot running group was found to have an increase in both gluteus medius activation and TFL activation, with the former showing greater change. These results may be interpreted as showing shod running to increase TFL activation and decrease gluteus medius activation. Whereas barefoot running increased both TFL and gluteus medius activation with a greater degree exhibited with gluteus medius. This may be attributed to a combination of the kinematic changes seen with forefoot and rearfoot striking and the effect of footwear on the human kinetic chain.

Limitations

Limitations affecting this study include: pre-test and post-test EMG placement, participants missing training days, participant fitness levels, limited time constraints, and sample size. Pre-test and post-test EMG placement cannot be directly compared due change in placement. Even a small amount of change in the placement of an electrode from pre to post testing could result in differences in EMG readings due to changes in electrical currents. Secondly, due to busy schedules if participants were unable to attend a training session they were asked to complete training on their own which would often include running in alternative environments increasing the amount of inconsistencies in training. Third, patient's fitness levels varied which could create a ceiling effect for participants who are more well trained, while gains for patients who are less trained could see increased training effects, altering the amount of neuromuscular activity. Furthermore, training time was limited to twice a week for six weeks due to scheduling conflicts for participants in physical therapy school. A longer or more frequent training period may have allowed for more significant neuromuscular changes. Lastly, the power of this study was limited due to a small sample size (n=22). This limitation can be contributed to participants being physical therapy students which would not allow for a diverse sample.

Adverse Effects

During the duration of the study no patients dropped out due to adverse events. However, during the training portion two participants reported minor orthopedic conditions including: pretibial periostitis and fibularis tendinopathy.

Participant reporting pretibial periostitis expressed chronicity of the injury from past running programs.

Overall, two participants were unable to complete the training program due to conditions unrelated to the study. One participant dropped out due to a newly discovered medical condition limiting their participation in physical activity. A second participant dropped out due to an injury sustained during a sporting event.

Recommendations for Future Research

Need exists for further randomized controlled trials with systematic methodology to investigate the effects of shod and barefoot running due to the incidence and prevalence of injury with running activities. Specifically, tensor fascia latae in comparison to gluteus medius. The findings examined in our study, although not statistically significant, suggest there is a change in muscular activity favoring increased gluteus medius and tensor fascia latae activity with barefoot running. Furthermore, there are copious amounts of research investigating the level of gluteus medius activity in relation to barefoot running, however there remains a void in regard to the tensor fascia latae and barefoot training.

APPENDIX A: INFORMED CONSENT

INFORMED CONSENT DOCUMENT TEMPLATE: NON-MEDICAL PROJECTS

IC 701-B

THE UNIVERSITY of NORTH DAKOTA
INSTRUCTIONS FOR WRITING AN INFORMED CONSENT DOCUMENT
NON-MEDICAL CONSENT TEMPLATE

INSTRUCTIONS:

- This consent document template is recommended for non-medical studies because it contains all required elements of consent.

- The text in bold throughout this document offers suggestions and guidance. It should be deleted and replaced with information specific to your study. The headers and footers are not meant to be edited and should remain on your consent document.

CONSENT DOCUMENT INSTRUCTIONS:

- Consent documents should be written in the second person (e.g., "You are invited to participate"). Use of the first person (e.g., "I understand that…") can be interpreted as suggestive and can constitute coercive influence over a subject.

- The consent form should be written at about an eighth grade reading level. Clearly define complicated terms and put technical jargon in lay terms.

- The consent form must be signed and dated by the subject or the subject's legally authorized representative. The signed consent from each subject must be retained by the investigator and a copy of the consent form must be provided to the subject.

CONSENT DOCUMENT FORMAT:

- To facilitate the IRB review process, the sample format below is recommended for consent forms.

- Prepare the entire document in 12 point type, with no blank pages or large blank spaces/paragraphs, except for a 2 inch by 2 ½ inch blank space on the bottom of each page of the consent form for the IRB approval stamp.

- Multiple page consent documents should contain page numbers and a place for the subject to initial each page.

ASSISTANCE

- If you have questions about or need assistance with writing an informed consent please call the Institutional Review Board office at 701 777-4279.

THE UNIVERSITY OF NORTH DAKOTA
CONSENT TO PARTICIPATE IN RESEARCH

TITLE: *Barefoot versus Shod Running: Training Effects on Navicular Drop and Foot Pressure Analysis*

PROJECT DIRECTOR: *Gary Schindler*

PHONE # *701-777-6081*

DEPARTMENT: *Physical Therapy*

STATEMENT OF RESEARCH

A person who is to participate in the research must give his or her informed consent to such participation. This consent must be based on an understanding of the nature and risks of the research. This document provides information that is important for this understanding. Research projects include only subjects who choose to take part. Please take your time in making your decision as to whether to participate. If you have questions at any time, please ask.

WHAT IS THE PURPOSE OF THIS STUDY?

You are invited to be in a research study that is interested in investigating how training barefoot running versus shod (shoe) running effects navicular drop (the amount that the navicular bone drops to the ground with weight bearing activities) and surface Electromyography (EMG) activity of the Tensor Fasciae Latae (TFL) and Gluteus Medius (GM) during waling and running activities. Literature identifies the barefoot runners complete more of a forefoot strike than shod runners (rear foot) which can lead to more gastrocnemius (calf) activation creating more supinated (walking/running more on the outside of the foot) foot mechanics. In addition, literature has not investigated the EMG activity of GM and TFL musculature during barefoot walking and running. This study aims to investigate whether training in barefoot running versus shod running reduces the amount of navicular drop and surface EMG activity of the TFL muscle while increasing EMG activity of the GM muscle during walking and running activities. You have been identified as a potential participant because you are a first, second, or third-year physical therapy, athletic training, or occupational therapy student at the University of North Dakota, a novice runner (0-20 miles per week), and meet this study's inclusion criterion.

The purpose of this research study is to understand what effect barefoot training has on navicular motion and EMG activity of the TFL and GM muscles during walking and running activities, which may assist in future injury prevention.

HOW MANY PEOPLE WILL PARTICIPATE?

A minimum of 6 participants will be take part in this study at the University of North Dakota. Each participant will be randomly placed in either the shoe running group or barefoot running group with each group having a minimum of 3 participants. Each group will complete pre- and post-test navicular drop, walking/running analysis utilizing the VICON motion analysis system, and surface EMG of the TFL/GM muscles during shod/barefoot walking and running and complete a post-survey analysis to determine compliance and training schedule. The Vicon Motion Analysis system utilizes 10 separate cameras in order to obtain a 3D motion analysis image of lever arms and joints. This system will assist in detecting the amount and speed of navicular drop and measure changes in pelvis and knee angles during barefoot walking/running activities between training groups. In between the pre- and post-tests each individual will complete a 6-week training schedule involving running on a treadmill with a gradual progression of distance and time per week as symptoms allow. Surveys will be completed at the time of the post-testing at the Hyslop Sports Center on the campus of the University of North Dakota.

HOW LONG WILL I BE IN THIS STUDY?

Your participation in the study will last approximately 8 weeks. Each participant will complete a pre-test navicular drop test, a walking/running analysis utilizing the Vicon Motion Analysis system, and surface EMG analysis of the TFL and GM during shod and barefoot walking/running. Following the pre-testing, each participant will complete a 6-week training program in either the barefoot running or shod running groups with a gradual progression of both distance and time per week as symptoms allow. Following the 6-week training period, each participant will complete a post-test navicular drop test, a walking/running analysis utilizing the Vicon Motion

Analysis system, and surface EMG analysis of the TFL and GM during shod and barefoot walking/running and complete a post-survey analysis to determine compliance and training schedule.

WHAT WILL HAPPEN DURING THIS STUDY?

Those who choose to participate will be screened to determine qualification to participate in the study according to the inclusion criteria which includes: no significant injury in the lower extremities in the past 6-months, age between 18-35, greater than 7 mm navicular drop, must be a rear foot striker, no current use of NSAIDs, no cardiopulmonary pathologies or significant medical history, and must currently complete between 0-20 miles of running per week. If you are included in this research, this study will take place over approximately an 8-week period. A bilateral navicular drop test, foot/pelvis motion analysis utilizing the Vicon Motion Analysis system, and surface EMG of your TFL and GM musculature will be performed on you during shod/barefoot walking and running prior to beginning the program. Then you will be randomly placed into either the barefoot or shod group. Each group will complete the same 6-week training program. You will run 2 mornings per week (Tuesday and Thursday) progressing from 10 minutes per session during the first week to 20 minutes per session upon week 6 resulting in 2-minute increment increases per week. After completing the program, a navicular drop test, foot/pelvis motion analysis, and surface EMG of TFL/GM musculature will be performed again. In addition, each participant will complete a post-program survey. No personal identifications are used on any written document and all descriptions of participants are anonymous. Participants are allowed to skip any questions in the survey that he/she would prefer not to answer.

WHAT ARE THE RISKS OF THE STUDY?

There are no foreseeable risks of physical, emotional, or financial risks to the participants with this study; however, since physical activity is taking place there may be a chance of muscle strains, fatigue, tendinitis, stress fractures, delayed onset muscle soreness (DOMS), or a general pain response, but minimal risk is anticipated. A certified athletic trainer, licensed physical therapist, sports/orthopedic specialist, and certified strength and conditioning specialist will be on site for all training sessions to answer any questions and to direct activity progression to limit adverse reactions. If adverse reactions occur the participant will be evaluated by the primary investigator and will be referred for further medical evaluation if deemed necessary.

WHAT ARE THE BENEFITS OF THIS STUDY?

Each participant may not benefit personally from being in this study. It is possible that the participants may see a decrease in static/dynamic navicular drop, decreased TFL EMG activity, and increased GM EMG activity, which may aid in injury prevention. Participants may also see improved cardiorespiratory fitness and a decrease in BMI. Also, we hope that in the future other people might benefit because a better understanding of how barefoot running training may affect navicular placement and movement and alter foot pressure, which may assist in reduced pain, improved function, and prevention of future overuse injuries for some patients. It will also provide evidence supporting or refuting the impact barefoot running training may have on arch dynamics, while TFL/GM EMG activity between shod runners and barefoot runners. This research may impact how physical therapists practice clinically, therefore impacting the lives of their patients and their families. This research may lead to alterations in exercise training that may lead to less future injuries.

WILL IT COST ME ANYTHING TO BE IN THIS STUDY?

You will not have any costs for participating in this research study.

WILL I BE PAID FOR PARTICIPATING?

You will not be paid for participating in this research study.

WHO IS FUNDING THE STUDY?

No funding is needed for this study. The University of North Dakota and the research team are receiving no payments from any agencies, organizations, or companies to conduct this research study. The 6-week training will take place at the High Performance Center on the campus of the University of North Dakota.

CONFIDENTIALITY

The records of this study will be kept private to the extent permitted by law. In any report about this study that might be published, you will not be identified. Your study record may be reviewed by Government agencies, the UND Research Development and Compliance office, and the University of North Dakota Institutional Review Board.

Any information that is obtained in this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. You should know, however, that there are some circumstances in which we may have to show your information to other people. For example, the law may require us to show your information to a court or to tell authorities if we believe you have abused a child, or you pose a danger to yourself or someone else. Confidentiality will be maintained with anonymous surveys conducted. All data collections will be kept anonymous by means of a 5-digit code that will include the participant's mother's or father's day of birth and the last three digits of their zip code while in high school. Consent forms will be kept in a locked and secure location for a minimum of three years, with only Gary Schindler having access to the consent forms and personal data.

If we write a report or article about this study, we will describe the study results in a summarized manner so that you cannot be identified.

IS THIS STUDY VOLUNTARY?

Your participation is voluntary. You may choose not to participate or you may discontinue your participation at any time without penalty or loss of benefits to which you are otherwise entitled. Your decision whether or not to participate will not affect your current or future relations with the University of North Dakota.

If you decide to leave the study early, we ask that you inform Gary Schindler that you would like to withdraw.

CONTACTS AND QUESTIONS?

The researchers conducting this study are Gary Schindler. You may ask any questions you have now. If you later have questions, concerns, or complaints about the research please contact Gary Schindler at 701-777-6081 or at gary.schindler@med.und.edu.

If you have questions regarding your rights as a research subject, you may contact The University of North Dakota Institutional Review Board at (701) 777-4279 or UND.irb@research.UND.edu.

- You may also call this number about any problems, complaints, or concerns you have about this research study.
- You may also call this number if you cannot reach research staff, or you wish to talk with someone who is independent of the research team.
- General information about being a research subject can be found by clicking "Information for Research Participants" on the web site: http://und.edu/research/resources/human-subjects/research-participants.cfm

Your signature indicates that this research study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

Subjects Name: ____

_____________________________ ________________

Signature of Subject Date

I have discussed the above points with the subject or, where appropriate, with the subject's legally authorized representative.

________________________________ __________________

Signature of Person Who Obtained Consent Date

REFERENCES

1. Lieberman DE, Bramble DM. The evolution of marathon running. *Sports Med*. 2007;37(4-5):288-290. doi: 10.2165/00007256-200737040-00004.
2. Liebenberg L. The relevance of persistence hunting to human evolution. *J Hum Evol*. 2008;55(6):1156-1159. doi: 10.1016/j.jhevol.2008.07.004.
3. Rothschild CE. Primitive running: A survey analysis of runners' interest, participation, and implementation. *J Strength Cond Res*. 2012;26(8):2021-2026.
4. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Br J Sports Med*. 2007;41(8):469-480. doi: 10.1136/bjsm.2006.033548.
5. Videbæk S, Bueno AM, Nielsen RO, Rasmussen S. Incidence of running-related injuries per 1000 h of running in different types of runners: A systematic review and meta-analysis. *Sports Med*. 2015;45(7):1017-1026. doi: 10.1007/s40279-015-0333-8.
6. Esculier J, Dubois B, Dionne CE, Leblond J, Roy J. A consensus definition and rating scale for minimalist shoes. *J Foot Ankle Res*. 2015;8(1):42.
7. Breine B, Malcolm P, Van Caekenberghe I, Fiers P, Frederick EC, De Clercq D. Initial foot contact and related kinematics affect impact loading rate in running. *J Sports Sci*. 2016;1-9.

8. Olney SJ, Eng J. Gait. In: Levangie PK, Norkin CC. eds. Joint Structure and Function: A Comprehensive Analysis, 5e New York, NY: McGraw-Hill; http://fadavispt.mhmedical.com/content.aspx?bookid=1862§ionid=1360867.
9. Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S., … & Pitsiladis, Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*. 2010;463:531–535.
10. Thompson MA, Lee SS, Seegmiller J, McGowan CP. Kinematic and kinetic comparison of barefoot and shod running in mid/forefoot and rearfoot strike runners. *Gait Posture*. 2015;41(4):957-959. Accessed Mar 21, 2018. doi: 10.1016/j.gaitpost.2015.03.002.
11. Lower limb dynamics vary in shod runners who acutely transition to barefoot running. *J of Biomech*. 2016;49(2):284-288. https://www-sciencedirect-com.ezproxy.library.und.edu/science/article/pii/S0021929015007034. doi: 10.1016/j.jbiomech.2015.12.002.
12. Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE. Foot strike and injury rates in endurance runners: A retrospective study. *Med & Sci in Sp & Ex* 2012;44(7):1325-1334. https://insights.ovid.com/pubmed?pmid=22217561. doi: 10.1249/MSS.0b013e3182465115.
13. Sinclair J, Richards J, Selfe J, Fau-Goodwin J, Shore H. The influence of minimalist and maximalist footwear on patellofemoral kinetics during running. *J Appl Biomech*. 2016;32(4):359-364.
14. Thompson MA, Lee SS, Seegmiller J, McGowan CP. Kinematic and kinetic comparison of barefoot and shod running in mid/forefoot and rearfoot strike runners. *Gait Posture*. 2015;41(4):957-959. doi: 10.1016/j.gaitpost.2015.03.002.

15. Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE. Foot strike and injury rates in endurance runners: A retrospective study. *Med Sci Sport Exer* 2012;44(7):1325-1334. https://insights.ovid.com/pubmed?pmid=22217561. doi: 10.1249/MSS.0b013e3182465115.

16. Fields KB. Running injuries: Changing trends and demographics. *Curr Sports Med Rep*. 2011;10(5):299-303.

17. Niemuth P, Johnson R, Myers M, Thieman T. Hip muscle weakness and overuse injuries in recreational runners. *Clin J Sport Med*. 2005;15(1):14-21. doi: 10.1097/00042752- 200501000-00004.

18. Maffulli N, Khan KM, Puddu G. Overuse tendon conditions: Time to change a confusing terminology. *Arthroscopy*. 1998;14(8):840-843.

19. Breine B, Malcolm P, Van Caekenberghe I, Fiers P, Frederick EC, De Clercq D. Initial foot contact and related kinematics affect impact loading rate in running. J Sports Sci. 2016;1-9.

20. Thompson MA, Lee SS, Seegmiller J, McGowan CP. Kinematic and kinetic comparison of barefoot and shod running in mid/forefoot and rearfoot strike runners. Gait Posture. 2015;41(4):957-959. Accessed Mar 22, 2018. doi: 10.1016/j.gaitpost.2015.03.002.

21. McCarthy C, Fleming N, Donne B, Blanksby B. Barefoot running and hip kinematics: Good news for the knee? *Med Sci Sports Exerc*. 2015;47(5):1009-1016. doi: 10.1249/MSS.0000000000000505.

22. Ekizos A, Santuz A, Arampatzis A. Transition from shod to barefoot alters dynamic stability during running. *Gait & Posture*. 2017;56:31-36.

23. Thompson M, Seegmiller J, McGowan CP. Impact accelerations of barefoot and shod running. *IJSM*. 2016;37(5):364-368.

24. Bonacci J, Vicenzino B, Spratford W, Collins P. Take your shoes off to reduce patellofemoral joint stress during running. *British Journal of Sports Medicine*. 2014;48(6):i70.

25. Sinclair J. Effects of barefoot and barefoot inspired footwear on knee and ankle loading during running. *Clinical Biomechanics*. 2014;29(4):395-399.

26. Semciw A, Neate R, Pizzari T. Running related gluteus medius function in health and injury: A systematic review with meta-analysis. *J Electromyogr Kinesiol*. 2016;30:98-110. doi: 10.1016/j.jelekin.2016.06.005.

27. Lenhart R, Thelen D, Heiderscheit B. Hip muscle loads during running at various step rates. *J Orthop Sports Phys Ther*. 2014;44(10):4. doi: 10.2519/jospt.2014.5575.

28. Tam N, Tucker R, Astephen Wilson JL. Individual responses to a barefoot running program: Insight into risk of injury. *Am J Sports Med*. 2016;44(3):777-784. doi: 10.1177/0363546515620584.

29. Ferber R, Bolgla L, Earl-Boehm JE, Emery C, Hamstra-Wright K. Strengthening of the hip and core versus knee muscles for the treatment of patellofemoral pain: A multicenter randomized controlled trial. *J Athl Train*. 2015;50(4):366-377. doi: 10.4085/1062-6050-49.3.70.

30. Bonacci J, Vicenzino B, Spratford W, Collins P. Take your shoes off to reduce patellofemoral joint stress during running. *Br J Sports Med*. 2014;48(6):425-428. doi: 10.1136/bjsports-2013-092160.

31. Barton CJ, Lack S, Malliaras P, Morrissey D. Gluteal muscle activity and patellofemoral pain syndrome: A systematic review. *Br J Sports Med*. 2013;47(4):207-214. doi: 10.1136/bjsports-2012-090953.

32. Woolf SK, Barfield WR, Nietert PJ, Mainous AG, Glaser JA. The cooper river bridge run study of low back pain in runners and walkers. *J South Orthop Assoc*. 2002;11(3):136-143.

33. Driscoll T, Jacklyn G, Orchard J, et al. The global burden of occupationally related low back pain: Estimates from the global burden of disease 2010 study. *Ann Rheum Dis*.

34. Cai C, Yang Y, Kong PW. Comparison of lower limb and back exercises for runners with chronic low back pain. *Med Sci Sports Exerc*. 2017;49(12):2374-2384. doi: 10.1249/MSS.0000000000001396.

35. Lee S, Bailey JP, Smith JA, Barton S, Brown D, Joyce T. Adaptations of lumbar biomechanics after four weeks of running training with minimalist footwear and technique guidance: Implications for running-related lower back pain. *Phys Ther Sport*. 2018;29:101-107. Accessed Mar 22, 2018. doi: 10.1016/j.ptsp.2016.11.004.

36. van der Hulst M, Vollenbroek-Hutten MM, Rietman JS, Schaake L, Groothuis-Oudshoorn KG, Hermens HJ. Back muscle activation patterns in chronic low back pain during walking: A "guarding" hypothesis. *Clin J Pain*. 2010;26(1):30-37. doi: 10.1097/AJP.0b013e3181b40eca.

37. Ogbonmwan I, Kumar BD, Paton B. New lower-limb gait biomechanical characteristics in individuals with achilles tendinopathy: A systematic review update. *Gait Posture*. 2018;62:146-156. Accessed Mar 22, 2018. doi: 10.1016/j.gaitpost.2018.03.010.

38. Cross M, Smith E, Hoy D, et al. The global burden of hip and knee osteoarthritis: Estimates from the global burden of disease 2010 study. *Ann Rheum Dis*. 2014;73(7):1323-1330. Accessed Mar 22, 2018. doi: 10.1136/annrheumdis-2013-204763.

39. Cibulka MT, Bloom NJ, Enseki KR, Macdonald CW, Woehrle J, McDonough CM. Hip pain and mobility deficits-hip osteoarthritis: Revision 2017. *J Orthop Sports Phys Ther*. 2017;47(6):A37. doi: 10.2519/jospt.2017.0301.

40. Dwyer MK, Stafford K, Mattacola CG, Uhl TL, Giordani M. Comparison of gluteus medius muscle activity during functional tasks in individuals with and without osteoarthritis of the hip joint. *Clin Biomech (Bristol, Avon)*. 2013;28(7):757-761. Accessed Mar 22, 2018. doi: 10.1016/j.clinbiomech.2013.07.007.

41. Sims KJ, Richardson CA, Brauer SG. Investigation of hip abductor activation in subjects with clinical unilateral hip osteoarthritis. *Ann Rheum Dis*. 2002;61(8):687-692. Accessed Apr 8, 2018.

42. Balshaw TG, Fry A, Maden-Wilkinson TM, Kong PW, Folland JP. Reliability of quadriceps surface electromyography measurements is improved by two vs. single site recordings. *Eur J Appl Physiol*. 2017;117(6):1085-1094. doi: 10.1007/s00421-017-3595-z.

43. Bussey MD, Aldabe D, Adhia D, Mani R. Reliability of surface electromyography activity of gluteal and hamstring muscles during sub-maximal and maximal voluntary isometric contractions. *Musculoskelet Sci Pract*. 2018;34:103-107. doi: 10.1016/j.msksp.2017.09.004.

44. Cram JR, Criswell E. *Cram's introduction to surface electromyography.* 2. ed. Sudbury,Mass. Jones and Bartlett; 2011:6; 248; 356; 358.

45. Eng CM, Arnold AS, Lieberman DE, Biewener AA. The capacity of the human iliotibial band to store elastic energy during running. J Biomech. 2015;48(12):3341-3348. Accessed Oct 15, 2018. doi: 10.1016/j.jbiomech.2015.06.017.