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The Investigation of the Influence of Long-Distance Running on Foot Volume in Healthy Female Collegiate Distance Athletes

Mufaro M. Hungwe

THE INVESTIGATION OF THE INFLUENCE OF LONG-DISTANCE RUNNING ON FOOT VOLUME IN HEALTHY FEMALE COLLEGIATE DISTANCE ATHLETES

By

Mufaro M. Hungwe

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Mufaro M. Hungwe

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John Mercer, Ph.D.
Examination Committee Chair

Julia Freedman Silvernail, Ph.D.
Examination Committee Member

Tedd Girouard, MS
Examination Committee Member

Jennifer Pharr, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Dean

ABSTRACT

The purpose of this study was to determine the change, if any, in foot volume over time after exercise, specifically a long-distance 5 Km run. Five UNLV Women's Track & Field and Cross-Country distance athletes (n = 5; 20 ± 1.87 years; 54.50 ± 3.71 kg; 160.88 ± 4.98 cm) were recruited to participate in this study. The dependent variables were foot volume and foot size. These variables were measured pre and post a 5 Km run at a self-selected somewhat hard pace over the independent variable time. Foot volumetrics were performed five times, (Pre-run, post-run$_{(5\ min)}$, post-run$_{(10\ min)}$, post-run$_{(15\ min)}$, post-run$_{(20\ min)}$) using a Foot Lucite Volumeter. Similarly, actual foot size was measured five times (Pre-run, post-run$_{(5\ min)}$, post-run$_{(10\ min)}$, post-run$_{(15\ min)}$, post-run$_{(20\ min)}$) using a Brannock Device® . Two repeated measures ANOVA were run using SPSS statistical package for Windows version Fix Pack 1 and an omnibus F-ratio was calculated to determine significance. Foot volume was influenced by the main effect of time *($p < 0.05$).* Using Simple-effect post-hoc tests, it was determined that foot volume at pre-run was not different to post-run$_{(5\ min)}$ nor post-run$_{(20\ min)}$ ($p > 0.05$). However, foot volume at pre-run was different from post-run$_{(10\ min)}$ and post-run$_{(15\ min)}$ ($p < 0.05$). Foot size was not influenced by the main effect of time *($p > 0.05$).* A Pearson product moment correlation (r) was used to assess the relationship between pre-run foot size and pre-run foot volume. A moderate positive correlation between pre-run foot size and pre-run foot volume ($r(5) = 0.42$) was observed. However, the moderate positive correlation between pre-run foot size and pre-run foot volume was not statistically significant,($p < 0.05$). The results from this study highlighted the importance of determining the moment in time that the foot volume is measured post a 5 km run as a way to understand the influence of exercise on foot volume. However, additional research is needed to fully understand the exact mechanism causing the change in foot volume.

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CHAPTER 1: INTRODUCTION

It is common for distance athletes to wear running shoes bigger than their normal shoe size by a half size or more. This practice is based on the premise that feet will swell (increase in volume) during exercise. Foot volume increases approximately 5% during the day and up to 8% following exercise, which necessitates leaving between 0.5 to 0.625 inches of space in front of the longest toe when fitting shoes on athletes (Chalk, McPoil, & Cornwall, 1995). The swelling of the foot (hereafter described as an increase in volume) is otherwise known as edema.

Taber's medical dictionary defines edema as a local or generalized condition in which body tissues contain an excessive amount of tissue fluid in the interstitial spaces. To prevent edema, the venous system requires normal cardiac function, an appropriate pressure gradient, and patent veins (Ratchford & Evans, 2017). The appropriate pressure gradients are regulated by the calf muscle pump mechanism which moves blood and other fluids in and out of the calf via the contraction and relaxing of the calf and the surrounding muscles in the lower extremity (Ratchford & Evans, 2017). In the case of edema in the foot, a volume increase is thought to occur when the calf muscle pump is overwhelmed by the build-up of fluid in the lower extremity (Cloughley & Mawdsley, 1995).

The non-exercise related causes of edema in the foot are uncontroversial. It is well understood that edema in the foot can result from medical conditions, including deep and superficial vein thrombosis, neuropathy that results in a foot-drop, and diabetes (Ratchford & Evans, 2017; Deshpande, Harris-Hayes, & Schootman, 2008; Cho & Atwood, 2002). However, it is somewhat unclear whether edema in the foot results from physical activity, including exercise. Several research studies have looked at the relationship between exercise and edema in the foot and sought to determine if the physical activity results in an increase in foot volume

(Chalk, McPoil & Cornwall, 1995; Cloughley & Mawdsley, 1995; McWhorter et al., 2006, McWhorter et al., 2003). However, these studies have produced inconsistent results. While these studies employ similar methodology, a review of the methodology revealed that a gap exists in the current literature. Presently, no studies that address the timing of foot volumetric measurements after exercise to determine whether there is potentially delayed foot swelling. Therefore, the purpose of this study is to determine the change, if any, in foot volume and foot size over time after exercise, specifically a long-distance run.

Measuring and tracking of foot volume via multiple measurements after exercise is essential (i) because it may reveal a correlation between overall shoe fit (the relationship between actual foot size and shoe size) and the onset of edema after exercise, especially in cases where there is a mismatch between true foot size, true shoe size, and preferred shoe size, (ii) to identify if edema occurs at any point after exercise and to determine if there is a potential of late onset edema after exercise, and (iii) to assist in preventing further exacerbation of orthopedic problems such as the traumatizing of the joints of the foot particularly the metatarsophalangeal joints associated with running. This last point is significant in situations where athletes may wear a shoe size that does not match their actual foot size, i.e., wearing a shoe that is too short, too tight, and/or too big.

CHAPTER 2: LITERATURE REVIEW

Introduction

On October 12, 2019, Eliud Kipchoge ran a sub-two-hour marathon and sent shockwaves through the running world. His official time of 1:59:40.2 was shocking because, like its predecessor, the four-minute mile, a barrier which Roger Bannister smashed on May 6, 1954, with a time of 3:59.4, a sub-two-hour marathon was believed to be impossible. Indeed, Kipchoge's first attempt in May 2017 fell short of the 2-hour mark by 26 seconds. Not long after that, on October 12, 2019, running enthusiasts, pundits and critics began asking whether Kipchoge had an unfair advantage. However, unlike most circumstances when records are broken, discussions did not center on whether Kipchoge had used performance enhancing drugs. Instead, the focus fell on the Nike shoes Kipchoge wore. Questions were asked of the design, including, but not limited to, the density and height of the shoe padding, whether the shoe had carbon fiber cores and, if so, how many, and the effect of the air bubbles that were positioned toward the toe-end of his shoe. So great was the brewing controversy surrounding the Nike shoe design that World Athletics, the international organization responsible for running, proclaimed that shoe technology could damage the integrity of running and introduced rules governing the shoes that elite athletes can wear in running competitions.

Interestingly, what was missing from the debate about Kipchoge's feat, was a discussion about the feet on which Kipchoge wore the shoes. Kipchoge wore a size 10.5 pair of Nike ZoomX Vaporfly NEXT% running shoes, but it is not clear if and how Nike employed any special testing to determine the fit of the shoes to Kipchoge's feet. As yet, there has been no disclosure about whether Nike measured the effect that running for nearly two hours at an average speed of 13 miles per hour would have on Kipchoge's foot volume and whether Nike saw fit to fit Kipchoge with a shoe size larger or smaller than his actual foot size. It is common to fit footwear to leave room between 0.5 to 0.625 inches of space in front of the longest toe (Chalk, McPoil, & Cornwall, 1995). According to Chalk et al., the volume of the foot increases approximately 5% during the day and up to 8% following exercise and a change in foot volume could result in the increase in foot length which necessitates the extra space in a running shoe (Chalk, McPoil, & Cornwall, 1995). The expansion of foot volume is thought to be edema (discussed in detail below), which is swelling caused by excess fluid trapped in the body's tissues. Edema of the foot is thought to occur when the body's circulatory system in the lower extremities fails to accomplish fluid balance.

It is understood that edema can result from non-exercise-related factors (discussed in detail below); however, it is somewhat unclear whether edema results from physical activity, including exercise. Several research studies have looked at the relationship between exercise and edema in the foot and sought to determine if physical activity results in an increase in foot volume (Chalk, McPoil & Cornwall, 1995; Cloughley & Mawdsley, 1995; McWhorter et al., 2006, McWhorter et al., 2003). However, these studies have produced inconsistent results. While these studies employ similar methodology, a review of the methodology revealed that a gap exists in the current literature. Presently, there are no studies that address the timing of foot volumetric measurements after exercise to determine whether there is a potential for delayed foot swelling. Therefore, the purpose of this research study is to determine the change, if any, in foot volume and foot size over time after exercise, specifically a long-distance run.

Edema and Causes of Edema

According to Merriam-Webster, edema is defined as an abnormal infiltration and excess accumulation of serous fluid in connective tissue or in a serous cavity. Edema has been found to contribute to the swelling of the foot in weight-bearing activities such as walking and running (Stick, Stiifen, & Witzleb, 1985). Therefore, it is important to identify running and non-running factors that can potentially cause edema. To prevent edema, the venous system requires normal cardiac function, an appropriate pressure gradient, and patent veins (Ratchford & Evans, 2017). In the lower extremities, the calf muscle pump plays a critical role in maintaining the appropriate intracellular pressure gradient and preventing edema through venous return and by overcoming gravity. It does this by removing 70% of blood out of the calf during walking, and as the calf relaxes, pressure gradients cause the flow of blood from the superficial veins into the deep system via communicating veins (Ratchford & Evans, 2017). Any disruption in the normal functioning of this system can lead to edema. An injury to the calf muscle, such as a gastrocnemius tear, could illustrate this disruption since the calf and the muscles that it houses are mainly responsible for maintaining intracellular pressure gradients (Ratchford & Evans, 2017). Similarly, a ruptured Baker's cyst presented by a crescent-shaped ecchymosis either at the popliteal joint, at the ankle or extending into the foot can also cause severe lower extremity edema (Ratchford & Evans, 2017).

Non-Exercise Induced Causes of Edema

Edema is widely understood to result from medical conditions such as deep and superficial vein thrombosis. These are commonly described as a pulling sensation in the calf and can occur as a result of a sudden trauma, surgery, hormone use, long haul travel, and/or family background of thromboembolism, and have been identified as potential causes of edema (Ratchford & Evans, 2017) (Cho & Atwood, 2002). These conditions can develop over long periods, such as during rest or after standing for long hours.

Another frequently overlooked cause of edema is neuropathy that results in a foot-drop[1] and subsequent calf muscle pump failure (Ratchford & Evans, 2017). A dysfunction in the

[1] An extended position of the foot caused by paralysis of the flexor muscles of the leg.

peripheral nerves as is often detected by numbness and tingling of the muscles that innervate the calf muscle, can lead to edema. Conditions of this nature like multiple sclerosis, stroke, and L5 radiculopathy have been reported to correlate with an imbalance in interstitial pressures as seen in edema. Similarly, diabetes has also been associated with nerve neuropathy, which, like neuropathy resulting from foot-drop, can cause adverse effects on lower extremities and can potentially cause edema. Diabetic peripheral neuropathy (DPN) has been described as one of the most severe complications of diabetes occurring in 30-50% of all diabetic patients (Deshpande, Harris-Hayes, & Schootman, 2008). In a study conducted by Chiles et al., peripheral nerve function partially mediates the relationship between diabetes and physical function (Chiles, et al., 2014). In this study, 1453 participants underwent a standard surface electroneurographic study of the right peroneal nerve, a test of vibration sensitivity at the level of the first metatarsal bone and a touch sensitivity of the external malleolus (Ferrucci, 2000). To assess the impact of diabetes status on nerve function collectively, peripheral neuropathy and Short Physical Performance Battery (SPPB) scores were calculated on a scale of 0-5 with higher scores indicating better physical function. It was concluded from this experiment that participants with diabetes had significantly lower SPPB values than their non-diabetic counterparts, suggesting that diabetes may be the cause of physiological changes, which in turn result in decreased lower-extremity function (Ferrucci, 2000). Thus, it was concluded that peripheral nerve dysfunction was a significant contributing factor to diabetes (Ferrucci, 2000).

Exercise-Induced Causes of Edema

The most significant amount of venous return from the lower extremity is through the deep veins that play a substantial role in weight-bearing activities (Chalk, McPoil, & Cornwall, 1995). In a static dependent leg, such as when standing still or sitting for an extended time, sustained high pressure in the veins can lead to an increase in capillary pressure and cause increases in foot volume, commonly identified as edema (Chalk, McPoil, & Cornwall, 1995). Muscular contraction of the lower extremity that occurs as a result of movement activates the calf muscle pump, which increases the rate at which blood is pumped out of the lower extremity towards the heart (Chalk, McPoil, & Cornwall, 1995). The increased pumping of blood through a series of one-way valves that prevent backflow to the feet, contributes to the overall maintenance of intracellular pressures in the lower extremity and works to prevent edema (Chalk, McPoil, & Cornwall, 1995). Ultimately this means, to avoid pooling of blood in the lower extremities, some form of muscular contraction must occur. This is supported by a study by Stegall, which used a mercury-in-silastic strain gauge to measure blood pressure in the saphenous vein at the ankle and found a significant decrease in venous blood pressure from more than 90 mmHg during relaxed standing to below 10 mmHg during running (Stegall, 1966). This study supported the theory that active contraction of the calf muscles and continuous activation of the muscle pump mechanism works to prevent increases in foot volume and therefore prevent edema.

The conclusion drawn by Stegall is further supported by that of Chalk et al. and Stick et al. In the Chalk et al. study, foot volumetrics of nine female volleyball players was measured before and after a 2-hr intense practice session that consisted of continuous running and jumping drills. Chalk et al. found that mean foot and calf volume in-fact decreased from 1,169.1 ml to 1,163.9 ml leading the study to conclude that the changes in foot volume measurements before and after the practice session was not statistically significant (Chalk, McPoil, & Cornwall, 1995). Decreases in calf volume observed in the Chalk et al. study were congruent with Stegall's results that noted a reduction in calf volume when subjects exercised. Because they found a statistically insignificant change in foot volume, Chalk et al. went further to conclude that it seemed unnecessary to account for anticipated changes in foot volume when fitting shoes for exercise activity (Chalk, McPoil, & Cornwall, 1995). However, they suggest that fitting shoes to include an extra 0.5 to 0.625-inch space in front of the longest toe could be necessary to accommodate anterior sliding of the foot during athletic activities (Chalk, McPoil, & Cornwall, 1995). Similarly, in the study by Stick et al., calf volume decreased following a 20-minute exercise where subjects went from sitting to exercising. However, prior to that, calf volume did initially increase in the first 2 minutes as subjects went from a recumbent position to standing due to the sudden increased filling of the capacity of the vessels (Stick, Stiifen, & Witzleb, 1985). This sudden increase was followed by a slow exponential increase in calf volume as subjects stood relaxed for 21 minutes in this position. This slow increase in calf volume could be explained by the lack of active lower extremity muscle contraction that would in turn activate the subsequent muscle pump mechanism, meaning failure to actively maintain the interstitial pressures would occur and foot volume would increase. However, as the subjects progressed from standing to performing the exercise that involved standing on their toes every 10 seconds following the rhythm of a time signal, calf volume decreased (Stick, Stiifen, & Witzleb, 1985). This can be attributed to the activation of the muscle pump mechanism that works to balance out these interstitial pressures and ultimately prevent edema, which is an explanation that is consistent with Chalk et al. and Stegall's results that noted a decrease in calf volume when subjects exercised.

On the other hand, studies by McWhorter et al. (2003), McWhorter et al. (2006), and Cloughley and Mawdsley (1995) produced results that supported contrary conclusions to those of Stegall and Chalk et al. on changes in foot volume as a result of exercise. These studies suggest that there are limits to the effectiveness of the muscle pump mechanism that works to prevent edema in the lower extremities through active muscle contraction, as seen in weight-bearing activities like walking and running. Instead, Cloughley and Mawdsley explain the potential increases in foot volume that occur after running as being caused by an overwhelming workload on the calf muscle pump, reducing its ability to balance interstitial pressures. They also proposed that edema can be caused by a disturbance in the mechanism that maintains interstitial fluid at an appropriate level, thereby causing an imbalance between filtration and absorption of fluid. In other words, if the volume of the fluid and macromolecules overwhelms the ability of the lymphatics to carry them away, edema may occur (Cloughley & Mawdsley, 1995). The findings of this study showed a significant mean increase of 31.2 ml after running and 17.9 ml after walking in foot and ankle volume. Although the primary purpose of this study was to compare the effects of 15 minutes of treadmill running to 15 minutes of treadmill walking on foot and ankle volume, overall increases in both walking and running were observed. Cloughley and Mawdsley attributed these increases in foot and ankle volumes to increased blood flow and increased transcapillary filtration of intravascular fluid (Cloughley & Mawdsley, 1995). This increase in transcapillary filtration was in turn observed to have resulted from the following factors: (a) an increase in microvascular pressure, (b) an increase in the microvascular surface area because of an increase in the number of open capillaries, and (c) an increase in total interstitial and intracellular osmotic pressure because of the formation of and release of metabolic products by the active muscle cells (Cloughley & Mawdsley, 1995) citing (Staub & Taylor, 1984).

In 2006, McWhorter et al. identified a gap in the literature and sought to determine the effect of body weight on the occurrence of edema in the lower extremity. The study categorized activities into one of two weight-bearing categories, loaded versus unloaded, whereby loaded activities referred to those where the lower extremities were required to support the body's entire weight and unloaded activities incorporated positions in which the lower extremities were required to support less than all of the body's total weight (McWhorter, et al., 2006). They categorized movement as either static, i.e., where no movement of lower extremities occurred, and dynamic, i.e., where the movement of lower extremities was essential. The activities compared were quiet standing versus walking on a treadmill and quiet sitting versus cycling on a stationary bike. Using the common water displacement method of volumetry, the authors demonstrated that the static conditions of standing and sitting produced significantly greater increases in foot volume compared to the dynamic conditions of treadmill walking and stationary bike cycling (McWhorter, et al., 2006). Additionally, they found that loaded conditions, as seen in treadmill walking and standing, produced significantly greater foot volume increases than the unloaded conditions of sitting and stationary bike cycling (McWhorter, et al., 2006). The study concluded that with loaded activities, the lower extremities were placed in a dependent position with most, if not all, of the body's forces being transmitted through the feet, thereby decreasing the ability of the venous system to pump blood back to the heart against gravity (McWhorter, et al., 2006). The study also found that unloaded dynamic activity as seen in stationary bike cycling resulted in a decrease in foot volume compared to loaded static and dynamic activities of standing and walking (McWhorter, et al., 2006). These findings support the reasoning that while biking, less body weight was being borne through the lower extremities and that more weight was instead being distributed through the pelvis. Similarly, this finding supports the idea proposed by Stegall that active contraction of surrounding musculature and continuous activation of the calf muscle pump works to prevent increases in foot volume and therefore prevent edema.

Conclusion

The discrepancies between the findings of Stegall, Chalk et al., and Stick et al., versus the results of Cloughley and Mawdsley, McWhorter et al. 2003, and McWhorter et al. 2006, could be explained by the limitations of the calf muscle pump mechanism in maintaining an equilibrium of interstitial pressure in the lower extremities. In the studies by Stegall, Chalk et al., and Stick et al., where edema was not found to occur after exercise, it is possible that the calf pump mechanism had not exceeded its optimal capacity to maintain fluid balance. Indeed, the noted decreases in foot volume in these studies might suggest that the calf muscle pump of the participants in those studies retained additional untapped capacity at the time foot volume was measured. Whereas, in the studies by Cloughley and Mawdsley, McWhorter et al. 2003, and McWhorter et al. 2006, the onset of edema after exercise was driven by the fluid balance demands of the activities in each study, thereby exceeding the optimal capacity of the calf muscle pump in the participants of those studies. This would be consistent with the non-exercise-related causes of edema, which involve circumstances where edema is directly caused by the muscle pump system, including the calf muscle pump, being compromised.

Notwithstanding the findings by Stegall, Chalk et al., and Stick et al., the majority of studies have found that exercise leads to increased foot volume (Cloughley & Mawdsley, 1995). Also, there is evidence that there is a positive correlation between exercise intensity and foot volume change after exercise whereby participants who engage in more intense weight-bearing activity are more likely to exhibit more significant foot volume increases (Cloughley & Mawdsley, 1995) (Lundvall, Mellander, Westling, & White, 1972).

However, in reviewing the literature it is apparent that there is little coverage on the relationship between shoe size and actual foot size (collectively referred to as shoe fit), in relation to edema. All the literature reviewed, except for the study by McWhorter et al. (2003), was silent on the issue of shoe fit. The McWhorter et al. (2003) study investigated the relationship between true foot size and preferred shoe size, based on a random sampling of five athletic stores. The study found that only one out of the five stores covered in the study, offered to take measurements of customers' feet to determine their true foot size and made recommendations based on those measurements (McWhorter, et al., 2003). Instead, the overwhelming majority of footwear employees fit customers with shoes based on the customers' preferences of comfort and not a proper fit. Consequently, McWhorter et al. (2003) found that it was common practice for store employees to recommend a shoe one full size greater than the measured shoe size (McWhorter, et al., 2003).

The McWhorter et al. (2003) study also focused on the relationship between running and walking foot volumetrics and their relationship with measured foot size and preferred shoe size (McWhorter, et al., 2003). The study measured foot volume before and after a 15-minute walk and before and after a 15-minute treadmill run. Interestingly, unlike the other studies reviewed in the literature herein, this was the only study to consider gender differences and the correlation between differences in foot size and shoe size, in measuring foot volume changes. Overall, the study found significant mean increases in foot volume after walking and after running in both men and women (McWhorter, et al., 2003). Concerning shoe fit, a positive correlation was noted between changes in volume during running and the differences between foot size and shoe size meaning there was a greater volume change when the shoe size was greater than the foot size (McWhorter, et al., 2003). Additionally, this study also found that measured foot size compared to preferred shoe size demonstrated a significant positive correlation whereby, when the measured difference between foot size and shoe size increased, there was a resultant increase in foot/ankle volume after exercise (McWhorter, et al., 2003). This finding suggests that shoe fit directly impacts the level of edema exhibited by a participant that has their foot volume measured immediately after exercise. Therefore, according to this study, wearing a bigger shoe during exercise could, in fact, cause foot and ankle swelling (McWhorter, et al., 2003). This swelling will likely be visible if the foot is measured immediately after exercise. On the contrary, McWhorter, et al. (2003) also noted that a shoe that is too short (decreased length) and/or too tight (decreased width) could significantly compress the foot. It is therefore likely that a participant wearing a shoe that is too short or too tight may not display any edema or accurate levels of edema if their foot volume is measured immediately after exercise.

In conclusion, a review of the literature has revealed no studies that measure the occurrence of edema in the foot over time after exercise. The methodology of all of the studies reviewed involved measuring foot volume only once immediately or shortly after exercise. Therefore, measuring and tracking of foot volume via multiple measurements after exercise is essential because (i) it may reveal a correlation between overall shoe fit (the relationship between true foot size and shoe size) and the onset of edema after exercise, especially in cases where there is a mismatch between true foot size, true shoe size, and preferred shoe size, (ii) to identify if edema occurs at any point after exercise and to determine if there is a potential of late-onset edema after exercise, and (iii) to assist in preventing further exacerbation of orthopedic problems such as the traumatizing of the joints of the foot particularly the metatarsophalangeal joints associated with running. This last point is essential in situations where athletes may wear a shoe size that does not match their true foot size i.e., wearing a shoe that is too short, too tight and/or too big.

CHAPTER 3: METHODS

Participants

Five female collegiate distance runners from the University of Nevada Las Vegas Women's Track and Field Team volunteered to participate in the study. The participants were between the ages of 18 and 24 years and reported no previous lower extremity/orthopedic injury in the past year. Participants were excluded from the study if they had sustained any ankle sprains or swelling, foot fractures and bone or joint disorders that could be aggravated by exercise. All participants were in track season and were running at least 3 days a week (approximately 50-60 miles a week). The experimental procedure was approved by the University of Nevada Las Vegas Institutional Review Board and each participant took a Physical Activity Readiness Questionnaire and signed an informed consent form prior to participating in the study.

Instrumentation

Foot Volumetrics were obtained using a Foot Lucite Volumeter (Figure 1) which comprised of a rectangular container, an obturator used to calibrate water levels prior to each measurement, a dry receptable cylinder used to collect the displaced water and a 1,000-mL graduated cylinder used to measure the volume of displaced water which indicated foot volume (Foot Volumeter, P.O. Box 146, Idyllwild, CA, 92349). Additionally, true foot size measurements were taken using a Brannock Device® (The Brannock Device Company, 116 Luther Ave, Liverpool, NY,13088, USA) which is a device commonly used for fitting of athletic footwear. Lastly, each participant was required to run in the Nike Zoom Pegasus 37 provided by the UNLV Athletic Department.

Several studies have established the reliability and validity of the use of the foot Lucite volumeter in measuring foot volumetry and detecting potential edema in the foot and ankle

(McWhorter, et al., 2003; McWhorter et al., 2006; Cloughley & Mawdsley, 1995; Moholkar & Fenelon, 2001).

Figure 1. Foot Lucite Volumeter used for measuring foot volume changes

Study Design/Procedures

To prevent potential foot volume increases associated with maintaining a static standing position while waiting to have their foot volumetrics measured before and after the run, each participant took part in the study on a specific day. Upon arrival pre-measurements were taken which consisted of age, height (cm) and weight (kg), shoe size, a description of how they were fitted for that size, the age of their shoes and what their dominant push-off leg was. Next, the participant was instructed to remove their shoes and socks and lie supine on a massage table and rest quietly for 10 minutes. During this time, each participant was briefed on the specifics of the study including how their measurements would be taken before and after their run.

Following this rest period, the participant was instructed to sit on a plinth where Resting Heart Rate (bpm) was immediately taken. Next, the pre-run foot volumetrics and foot size measurements were taken where the participant was instructed to slowly lower their foot into the volumeter until their posterior heel and calf touched the back of the volumeter and their foot was flat on the bottom. The participant sat still until all displaced water was collected in the dry receptable. The displaced water was then poured into the 1,000-mL graduated cylinder and volume was recorded in milliliters. After foot volumetrics were taken, the participant dried their foot and placed the heel of their dominant heel against the back of the Brannock Device® (The Brannock Device Company, 116 Luther Ave, Liverpool, NY, 13088, USA) to measure their true foot size.

After completing their pre-run measurements, the participant dried off their foot, put on their socks and shoes and began their normal 10-minute warm up routine. The participant then ran the 5 km run at their self-selected pace that was somewhat hard. Upon completion of the run, the participant immediately took off their sock and shoe of the same foot previously measured and placed their foot back in the assigned volumeter. The foot size measurements and foot volumetrics procedures were performed using the same pre-run methodology. However, after the run, foot size and foot volume of each participant were measured four times every 5 minutes and while they waited for foot volume to be recorded and for the volumeter to be reset, the participant was asked to place their feet on a secondary plinth to avoid excess pooling of fluid in the lower extremities until it was time to place their foot back into the volumeter.

Statistical Analysis

Data were analyzed using the SPSS statistical package for Windows® version Fix Pack 1. Means and standard deviations of the dependent variables which were foot volume and foot size were calculated. A one-way repeated measures ANOVA was used to determine whether or not foot volume and foot size were influenced by the independent variable time (Pre-run, post-run$_{(5\ min)}$, post-run$_{(10\ min)}$, post-run$_{(15\ min)}$, post-run$_{(20\ min)}$). An F-Ratio was calculated to assess the probability of rejecting the null hypothesis that identified that there would be no foot volume and/or foot size changes across time. The alpha level was set to 0.05. If the omnibus F-ratio was significant, simple effects post-hoc tests were computed comparing the pre-run condition to each of the other times. An effect size was calculated to determine the magnitude of the differences between means. Lastly, a Pearson product moment correlation (r) that was used to assess the relationship between pre-run foot size and pre-run foot volume.

CHAPTER 4: RESULTS

There were no outliers, as assessed by boxplot; foot volume and foot length data were normally distributed for each time variable, as assessed by Shapiro-Wilk test *($p > 0.05$);* and Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(9) = 10.08, p = 0.454$.

Foot Volume was influenced by the main effect of time ($F_{(4,16)} = 4.83, p = 0.01$, *partial* $\eta^2 = 0.55$, Figure 2). Using Simple Effect post-hoc tests, it was determined that foot volume at pre-run was not different to post-run$_{(5\ min)}$ ($p = 0.348$) nor post-run$_{(20\ min)}$ ($p = 0.06$). However, foot volume at pre-run was different from post-run$_{(10\ min)}$ ($p = 0.04$) and post-run$_{(15\ min)}$ ($p = 0.02$) (Table 1, Figure 2).

Foot size was not influenced by the main effect of time ($F_{(4,16)} = 1.00, p = 0.44$, *partial* $\eta^2 = 0.20$ Figure 3).

Additionally, there was a moderate positive correlation between pre-run foot size and pre-run foot volume, $r(5) = 0.42$, (Figure 4). However, the moderate positive correlation between pre-run foot size and pre-run foot volume was not statistically significant, $p = 0.49$ with pre-run foot size explaining 17% of the variation in the pre-run foot volume.

Table 1. Group Means ($\bar{x}$) and Standard Deviations (N = number of subjects) for foot volume (milliliters) for each time measurement. A 5 Km run was completed between the pre-run and post-run$_{(5\ min)}$ measurement. Each post-run measurement was taken 5 minutes apart. Note: * indicates that condition was different than Pre-Run foot volume ($p < 0.05$)

Time	Mean Foot Volume (ml)	Foot Volume Standard Deviation	Sig. Value
Pre-Run	809.00	80.50	
Post-Run$_{(5\ min)}$	829.40	42.67	0.348
Post-Run$_{(10\ min)}$	844.00*	75.70	0.044*
Post-Run$_{(15\ min)}$	858.00*	59.33	0.016*
Post-Run$_{(20\ min)}$	860.00	48.48	0.059

Table 2. Group Means ($\bar{x}$) and Standard Deviations (N = number of subjects) for foot size for each time measurement. A 5 Km run was completed between the pre-run and post-run measurements. Each post-run measurement was taken 5 minutes apart.

Time	Mean Foot Size	Foot Size Standard Deviation	N
Pre-Run	7.4	1.1937	5
Post-Run$_{(5\ min)}$	7.5	1.0607	5
Post-Run$_{(10\ min)}$	7.4	1.1937	5
Post-Run$_{(15\ min)}$	7.4	1.1937	5
Post-Run$_{(20\ min)}$	7.4	1.1937	5

Figure 2. Change in foot volume over time with standard deviations error bars. A 5 Km run was completed between the pre-run and post-run measurements. Each post-run measurement was taken 5 minutes apart. Note: * indicates that condition was different than Pre-Run foot volume ($p < 0.05$)

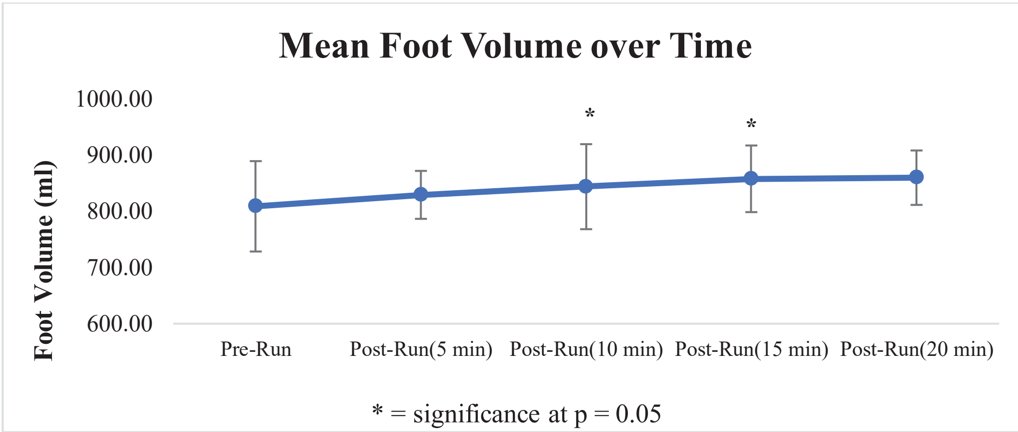


Figure 3. Change in foot size over time with standard deviations error bars. A 5 Km run was completed between the pre-run and post-run (1) measurement. Each post-run measurement was taken 5 minutes apart.

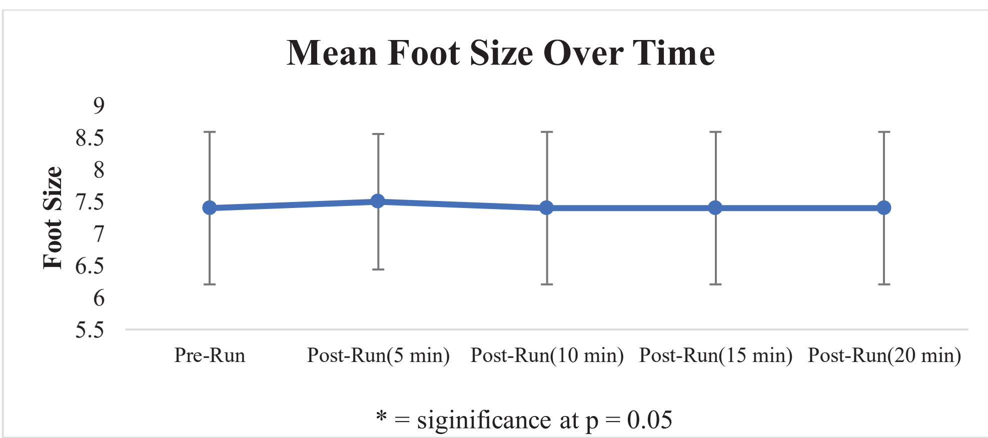
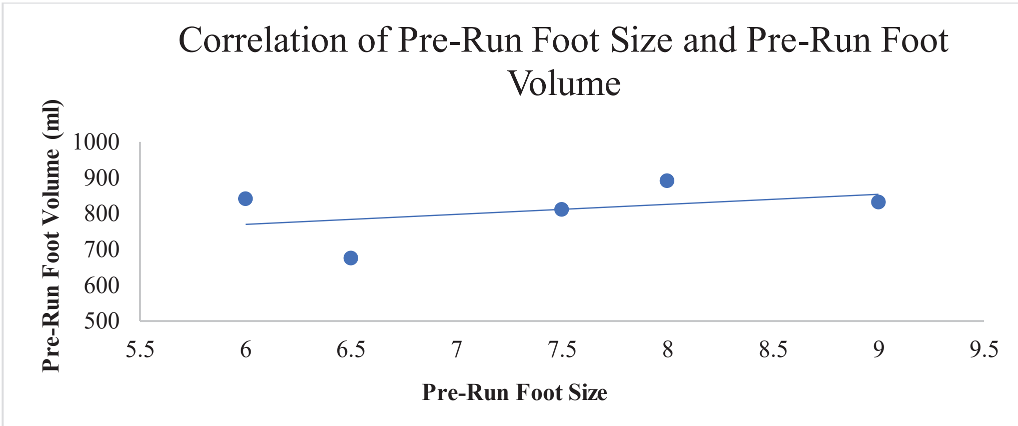


Figure 4. Correlation of Pre-Run foot size and Pre-Run foot volume



CHAPTER 5: DISCUSSION

There were two principal observations of this study. The first being that foot volume was influenced by the main effect of time. That is, there was a 4.32% increase in foot volume between pre-run and post-run$_{(10\ min)}$, and a 6.06% increase between pre-run and post-run$_{(15\ min)}$. However, there was no change in foot volume between pre-run and post-run$_{(5\ min)}$ and between pre-run and post-run$_{(20\ min)}$. Therefore, because foot volume was statistically significant different from pre-run and post-run$_{(10\ min)}$, ($p = 0.04$) and pre-run and post-run$_{(15\ min)}$, ($p = 0.02$), we rejected the null hypothesis that stated that foot volume did not change over time and accepted the alternative hypothesis that stated that foot volume did in fact change over time.

The second important observation of this study was that foot size defined as foot length was not influenced by the main effect of time, meaning that there was no change in the length of the foot over time. Along with the observation that foot length did not change, foot width did not change over time. Although width was not statistically tested, the width measured by letter scale – recorded for each time was the same per subject. Therefore, because foot size was not statistically different at all points in time, we failed to reject the null hypothesis that stated that foot size did not change over time, and we cannot accept the alternative hypothesis that stated that foot size would change over time.

The results of this study are congruent with those of McWhorter et al. (2003), McWhorter et al. (2006), and Cloughley and Mawdsley (1995). In those studies, it was reported that there were increases in foot volume after exercises such as walking, running, and loaded conditions as seen in treadmill walking and standing. McWhorter et al., (2003) reported a 2% foot volume increase pre and post a 15-minute treadmill walk and a 3% foot volume increase pre and post the 15-minute treadmill run. Similarly, in 2006 McWhorter et al. reported a 3% foot volume increase after a 15-minute treadmill walk and a 2% foot volume increase pre and post-quiet standing. These exercises that were defined as loaded conditions similar to that of running reported similar foot volume increase magnitudes similar to that of this present study. Cloughley & Mawdsley, (1995) also reported a mean foot volume increase of 31.2 ml after a 15-minute treadmill run which is within the range of the 35 ml foot volume increase seen between pre-run and post-run$_{(10\ min)}$ and the 49 ml foot volume increase between pre-run and post-run$_{(15\ min)}$ of this study.

The exact mechanism causing the change in volume of the foot after completing the 5 Km run is not entirely known. However, the results from these three studies (McWhorter, et al., 2003) (McWhorter, et al., 2006) (Cloughley & Mawdsley, 1995) combined with the results from the present study seem to provide evidence for the hypothesis that the calf-muscle pump mechanism is limited in the ability to balance interstitial pressures of the foot. Cloughley & Mawsdey, (1995) attributed the increase in foot volume to the inability of the calf-muscle pump to overcome the overwhelming workload of the exercise. That is, lower extremity edema as seen in foot swelling may be closely associated with a disturbance in the mechanism that maintained interstitial fluid at an appropriate level thereby causing an imbalance between filtration and absorption of fluid. In other words, if the volume of the fluid and macromolecules overwhelms the ability of the lymphatics to carry them away, edema in the form of foot swelling may occur (Cloughley & Mawdsley, 1995). Cloughley & Mawdsley, (1995) also concluded that foot volume increased as a result of an increase in blood flow and increase in transcapillary filtration that was in turn observed to have resulted from the following factors: (a) an increase in microvascular pressure, (b) an increase in microvascular surface area because of an increase in the number of open capillaries, and (c) an increase in total interstitial and intracellular osmotic pressure because of the formation of and release of metabolic products by the active muscle cells

(Cloughley & Mawdsley, 1995) citing (Staub & Taylor, 1984). Therefore, based on the analysis of the results of this present study, we hypothesize that the increase in foot volume between pre-run and post-run$_{(10\ min)}$ and pre-run and post-run$_{(15\ min)}$ after the 5 Km run in the participants of this study, can similarly be explained by the reduced ability of the calf muscle pump to balance maintain interstitial pressure balance as well as any of the three factors of transcapillary filtration described above. However, further research is needed to test the exact mechanism causing the change in volume of the foot after completing the 5 Km run.

The effect of body weight during a run as described by McWhorter et al., (2006) can be considered as an essential role in the changes in foot volume between pre-run and post-run$_{(10\ min)}$ and between pre-run and post-run$_{(15\ min)}$ observed in this study. The activity of walking, similar to that of running was identified by McWhorter et al. as a loaded condition whereby the lower extremities were required to support the entire body's weight. In their 2006 study, where treadmill walking was defined as a loaded condition, significant increases in foot volume were observed which led to the conclusion that with loaded activities, the lower extremities were placed in a dependent position with most, if not all, of the forces being transmitted through the feet, thereby decreasing the ability of the of the venous system to pump blood back to the heart against gravity (McWhorter, et al., 2006). Consequently, because running can also be classified as a loaded activity in which the lower extremities are placed in a dependent position with most, if not all, of the forces being transmitted through the feet, it reasonable to conclude that the act of running a 5 Km in this study, was strongly associated and may have resulted in the changes and increases in foot volume between pre-run and post-run$_{(10\ min)}$ and post-run$_{(15\ min)}$ values. However, future research involving running a 5 Km on a body-weight-supported treadmill, removing the influence of body weight on the run, may help identify the exact mechanism causing the change in volume of the foot after completing the 5 Km run.

On a similar note, the relationship between foot length and foot volume observed in the present study agrees with previous research work. For example, in the McWhorter et al. (2003) study, a positive correlation was noted between changes in foot volume during running and the differences between foot size and shoe size meaning there was a greater volume change when the shoe size was greater than the foot size (McWhorter, et al., 2003). This observation is congruent with the positive correlation between the pre-run foot size and the pre-run foot volume reported in this present study. More particularly, despite the fact that 40% of the participants wore the correct size shoe according to Brannock Device measurements, 20% of the participants in this present study wore a shoe that was a half a size bigger than their true foot size, and presented a 6.17% foot volume increase from pre-run to post-run$_{(10\ min)}$ and an 8.64% foot volume increase from pre-run to post-run$_{(15\ min)}$. Another 20% of the participants in this study wore a shoe that was a full size bigger than their true foot size and experienced a 2.38% foot volume increase between pre-run and post-run$_{(15\ min)}$. Furthermore, this present study reported similar results to that of McWhorter et al., (2003) in the sense that the last 20% of the group in this study who wore a shoe that was two sizes smaller than their true foot size, significantly compressed their foot, thereby, decreasing their foot volume by 1.20% immediately after the run (between pre-run and post-run$_{(5\ min)}$). However, a 3.61% increase in foot volume 5 minutes later (between pre-run and post-run$_{(10\ min)}$) and a 4.82% foot volume increase 10 minutes later (between pre-run and post-run$_{(15\ min)}$) was observed. This supports the idea that likely, a participant wearing a shoe that is too short (decreased length) or too tight (decreased width) may not display any foot swelling or accurate levels of foot swelling if their foot volume is measured immediately after exercise as seen in the McWhorter et al., (2003) study.

On the contrary, despite similar foot increases of this present study and those of McWhorter et al. (2003), McWhorter et al., (2006), and Cloughley and Mawdsley (1995), there was a disagreement in the main design of the experiment. This present study focused more on the time increments that foot volume measurements were made after the run, which is critical information in understanding the influence of exercise on foot volume. The previously explained studies (McWhorter, et al., 2003) (McWhorter, et al., 2006) (Cloughley & Mawdsley, 1995) however, did not factor in time in their experimental design. For example, this present study specifically focused on factoring in and stating the exact time (every 5 minutes) each foot volume measurement was taken, particularly between the end of the 5 Km run and the first-foot volume measurement, which is a point the other three studies omitted from their experimental design. Additionally, this present study measured foot volume four times after the run to factor in any further foot volume increases after the initial foot volume measurement. The other studies only did one pre and one post-foot volume measurement. However, despite this design difference, overall foot volume increases were observed in all four studies affirming the limitations of the muscle pump mechanism in balancing interstitial pressures resulting from exercise and, more importantly, a running workload.

To take accurate volumetry measurements, numerous variables need to be considered. These variables include the environmental conditions present during the run, the time of day the study was conducted, the temperature of the water in the Foot Lucite Volumeter, potential fatigue of the participant, the way each participant’s shoelaces were tied throughout the study, the age of their shoes and most importantly whether the shoe size of the participant matched their true foot size. Although several of these confounding factors were considered in the study's design, it was important to have the participants run as close to their normal conditions as possible to get an accurate representation of how their body would react after running a 5 Km. To offset some of the confounding factors, participants were required to be fully rested at least 24 hours prior to their run to offset any fatigue from previous practice runs done earlier that week. Tepid water temperatures between 20 and 35°C were maintained as this range of water temperature has been shown not to significantly increase or decrease volume measurements (McWhorter, et al., 2006) citing (King, 1993) (McCulloch & Boyd, 1992) (Sims, 1986). Additionally, both Moholkar & Fenelon, (2001) and Nilsson & Bjerknes Haugen, (1981) have shown that the time of day does not have any significant effect on the measurement of extremities (Moholkar & Fenelon, 2001) (Nilsson & Bjerknes Haugen, 1981).

Regarding the shoelace tying mechanism, we chose to allow all participants to tie their shoelaces the same way they would before a typical 5 Km run during practice to mimic their usual running conditions. This means that there may have been a potential effect on the foot volumetry measurement results by allowing unique shoelace tying. Furthermore, it was considered that each participant might have untied their shoelaces at any point throughout the experiment, particularly during the run. To control this confounding factor in future research, an adequate lacing method of shoelace tying can be introduced where each participant would be required to tie their laces using this method, and each participant would be given clear instructions not to untie their laces at any point during the run, until just before foot volume and foot size measurements. Additional research is needed to better understand the influence of these different factors on foot volume post-exercise.

Another confounding factor that was considered in the study's design was the total distance of the run and the course that each participant would run. A map of the running course was created to offset this factor, and each athlete was instructed to run the same course. Similarly, because of varying shoe age periods among the participants, it is not clear how shoe age and total shoe mileage influenced the study's outcome. Therefore, future research needs to consider shoe age and total shoe mileage as one of the independent variables measured to determine potential changes in the dependent variables foot volume and foot size.

Environmental factors such as the outside temperature were also another factor that was considered during the run portion of the experiment. The effect of extreme hot and cold temperatures on foot volume has been supported by other studies (McWhorter, et al., 2006) citing (King, 1993) (McCulloch & Boyd, 1992). However, because the study was conducted in late March when outside temperatures on testing day ranged from 52 - 64°F, the temperature was not considered as one of the variables that would affect foot volume by way of participant fluid loss (i.e., sweating). It was also conjectured that the hydration status of the participants was not considered in this study which is a factor that may have affected foot volume results. In a 2011 study by Bracher et al., (2011), it was reported that total fluid intake was positively related to changes in both arm and lower leg volumes where ultramarathon athletes with an increased fluid intake developed an increase in limb volumes (Bracher, 2011). It was noted that none of the participants drank water during the run, but some participants drank water before they arrived at the lab, some just before they started their run and some until after the post-run measurements were taken and the study had ended. It is not known if drinking water before the 5 Km run had any influence on post-run foot volumes. The importance of the present design was to simulate what an athlete would do pre/post run regarding fluid intake. Future research is needed to understand if taking in fluids influences foot volume.

Interpretation of Results

All factors considered and based upon the analysis, it is conjectured that while foot size characterized by foot length (arch length and heel-to-toe length) and foot width does not change over time as seen in (Table 2, Figure 3), all 5 participants had similar foot volume changes over time after a 5 Km run. However, because the foot did not get longer nor wider as a consequence of a 5 Km run, another dimension such a foot height, or foot circumference must be considered as the contributing factor to changes in foot volume observed between pre-run and post-run$_{(10\ min)}$ and pre-run and post-run$_{(15\ min)}$ values presented in this study.

From a practical application perspective, runners anecdotally want to know whether or not they should purchase a larger size shoe for an endurance run. Given the present study result that there is a moderate relationship between foot length and foot volume combined with previous research (e.g., McWhorter et al., 2003), there may be some rational behind the idea of using a larger shoe. Chalk, McPoil & Cornwall (1995) suggested to fit footwear with an extra 0.5 to 0.625 inches of space in front of the longest toe to accommodate anterior sliding of the foot during athletic activities. However, based on the results of this present study, the changes in foot volume were not associated with changes in foot length. Therefore, it would seem unnecessary to fit shoes that are longer in length solely based on the idea of foot swelling accommodations (characterized by foot length and foot width). However, if the person is comfortable having that little extra space in front of the longest toe to accommodate anterior sliding during running as reported by one of the participants in this study, then fitting a shoe with extra space in front of the longest toe seems adequate.

Limitations

Our study only measured 5 healthy NCAA Division I female collegiate distance athletes between the ages of 18-24 years old with a cumulative experience in long distance running. Therefore, the ability to generalize our results to the general public particularly males, special populations such as the geriatric and injured population, persons younger than the age of 18 and older than the age of 25 and those that are recreational runners is limited. Future research, involving a higher number of participants, a population group of both males and females, a population with a wider age range, and a population group of elite, amateur and recreational runners is recommended to get more generalizable results.

Conclusion

In conclusion, foot volume was influenced by a 5 Km run. Most importantly, it was determined that the moment in time that the foot volume is measured post a 5 km run is critical to understanding the influence of exercise on foot volume. Specifically, the foot volume immediately at the end of the run was not different than pre-run foot volume. However, foot volume at 5 and 10 minutes after the run had increased relative to the pre-run foot volume measurement. Interestingly, foot size was not influenced by the 5 Km run and remained unchanged during all measurements over the 20 min period post-run. Since foot volume changed but foot length and width did not, further research is needed to better understand which dimension of the foot may change post exercise. Furthermore, additional research is needed to fully understand the mechanism causing the change in foot volume. Finally, it is suggested that professionals fit runners with a shoe size that will accommodate anterior foot sliding instead of foot length increases and more importantly a shoe size that will allow runners the most comfortable run.

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CURRICULUM VITAE

Mufaro Hungwe
muffyhungwe@gmail.com | https://www.linkedin.com/in/mufarohungwe/ |Las Vegas, NV

Education

University of Nevada, Las Vegas — May 2021
M.S. in Kinesiology – Biomechanics (GPA: 3.70) — *Las Vegas, NV*

University of Nevada, Las Vegas — May 2019
B.S. in Kinesiology (GPA: 4.0) — *Las Vegas, NV*

Truman State University — Aug 2015 - May 2017
Exercise Science (GPA: 3.83) — *Kirksville, MO*

Technical Skills

Microsoft Office Suite, MATLAB, In-Built Kistler Force Plates, Vicon 3D Motion Capture, Structure Core Sensor 3D Scanning, Project Management, Shoe Impact Testing, EMG Cometa System, SPSS Software

Project Experience

Investigative Research - Graduate Thesis Project — *August 2020 – Present*

- Investigating the influence of long distance running on foot volume in healthy female collegiate distance athletes
- Cultivating project management skills by overseeing all areas of the project and ensuring successful completion
- Principal investigator in charge of organizing the performance testing of running footwear and biomechanics research protocols including pilot testing, data collection, summarizing and presentation of results
- Utilize SPSS Software to analyze collected foot volume data to present key perceptual information to running stores

Professional Development

Host & Organizer - Google Panel, UNLV Athletics — *November 2020*

- Organized and hosted a Google Panel that connected 30 student athletes with five Google professionals
- Assisted eight student athletes with networking skills and resume prepping which led to four follow-up interviews

Graduate Advisor - African Student Association — *Sept 2019 - May 2020*

- Advised and oversaw a team of 12 Executive Board members and aided in preparation of annual Fashion Show
- Pioneered entertainment recruitment and handled venue contracts for Fashion Show that hosted 500 guests
- Liaised between school administration and ASA Executive Board and 100 ASA members

Research Experience

Teaching and Research Graduate Assistant - Anatomy & Physiology Lab *Sept 2019 - May 2021*

- Instruct advanced Anatomy and Physiology lab material to 100 junior and senior university students

- Utilize Canvas to set bi-weekly exams and provide timely feedback to students
- Member of a team that liaises between 600 Anatomy & Physiology students and the Kinesiology administration
- Assist with IRB documentation, submissions, edits and management of approved Biomechanics study protocols

Biomechanics Student, Footwear Researcher - University of Nevada, Las Vegas *May 2018 - Aug 2018*

- Spearheaded a Biomechanics research project on muscle activity/responsiveness during a 100m block/sprint start
- Developed testing parameters and employed electromyography (EMG) as the key testing mechanism
- Measured the influence of shoe type (spikes vs. running shoes) and sprint experience on EMG muscle activity
- Normalized collected EMG data to muscular voluntary isometric contractions (MVIC) and used MATLAB and Microsoft Excel to analyze and summarize findings on compiled results
- Utilized Canva and Microsoft PowerPoint to create project deliverables presented as part of various statewide symposiums and research conferences

Internship Experience

Kinesiology Intern - High Performance Center, Pretoria, South Africa *June 2019 - Aug 2019*

- Performed body kinematic and kinetic tests on 60 athletes admitted into Cricket and Track & Field Programs
- Administered restoration programs that returned 5 post-knee surgery geriatric patients to full functional normalcy

Research Intern - Johnson & Johnson Research and Development, Spring House, Pennsylvania *May 2017 - Aug 2017*

- Assisted in the development of a company-wide wellness program that drove up employee engagement by 6%
- Analyzed collected data on employee engagement and provided feedback to J&J Board Executives

Extracurricular Involvement

Commencement Speaker & Valedictorian - UNLV Spring 2021 Graduation *Spring 2021*
Student Representative - UNLV Student Athlete Inclusion Initiative *Fall2020-Spring 2021*
NCAA Division I Athlete - UNLV Track & Field *Fall2017-Spring 2021*
Volunteer - Goodie Two Shoes Foundation *Fall2017-Spring 2021*
Graduate Advisor - African Student Association *Fall2017-Spring 2021*
Member - Phi Kappa Phi Honor Society *Spring2019-Present*
OHUB.SXSW Student Fellow - OHUB.SXSW *Spring 2021-Present*