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The Differences in Time to Stability, Foot Muscle Size,
and Toe Flexor Strength Between
Cheerleaders and Gymnasts

Kelsey Renee Garner

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

The Differences in Time to Stability, Foot Muscle Size, and Toe Flexor Strength Between Cheerleaders and Gymnasts

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Context: There has been recent speculation that the intrinsic muscles of the foot may play a larger role in lower extremity control and injury than previously believed. Multiple studies have shown that certain intrinsic muscles increase in size and strength after transitioning to minimalist shoe running, theoretically decreasing injury risk. There are currently no studies that examine the effect that training barefoot has in other athletic populations. **Objective:** Our purpose was to compare the intrinsic and extrinsic foot muscle size and strength in gymnasts (who predominantly train barefoot) and cheerleaders (who predominantly train shod). Another purpose was to measure time to stability for both groups shod and unshod. **Design:** Observational study. **Setting:** Human Performance Laboratory. **Participants:** 16 collegiate gymnasts (height = 159.3 ± 4.9 cm, weight = 56.7 ± 4.3 kg) and 16 collegiate cheerleaders (height = 161.9 ± 5.4 cm, weight = 58.7 ± 7.1 kg) volunteered for this study. **Main Outcome Measure(s):** The muscle size of 6 intrinsic and extrinsic muscles of the foot were measured using ultrasound, toe flexor strength, as assessed using a custom-made dynamometer, and time to stability following a drop landing, as assessed using ground reaction force data collected with force plates. **Results:** There were no significant group differences in great toe flexor strength ($p = 0.274$), lateral toe flexor strength ($p = 0.824$), or any of the time to stability conditions ($p = 0.086 - 0.90$). Only one muscle, fibularis longus, was significantly bigger in gymnasts than cheerleaders ($p = 0.017$). **Conclusions:** Our findings suggest that the barefoot training of gymnasts may not have as large of an impact on the foot musculature and strength as running barefoot or in minimalist shoes has on these factors.

Key Words: ultrasound, muscle size, toe flexor strength, time to stability, drop landing, gymnasts, cheerleaders

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INTRODUCTION

The intrinsic and extrinsic foot muscles work together to produce foot and ankle movements necessary for bipedal locomotion. These muscles help facilitate plantar flexion, metatarsophalangeal (MTP) flexion, MTP extension, and ankle dorsiflexion throughout stance-to-swing transition.¹ They also help produce supination and pronation of the subtalar joint. The plantar intrinsic muscles also play a role in stabilizing the medial longitudinal arch (MLA) throughout the functional phases of locomotion.^{2,3}

Recently, some researchers have speculated that these muscles may play a larger role in lower extremity control and lower extremity injury than traditionally believed. Tsai et al.⁴ observed in 45 subjects that those with a more pronated or supinated foot had less static postural control for single-limb stance than those with a neutral foot structure. A high arched foot structure, and more commonly a low arched foot structure, is commonly seen in athletes suffering from lower extremity injury.^{5,6} Some researchers believe that these muscles should receive more attention in the evaluation and rehabilitation of lower extremity injuries.^{4,7}

According to Mulligan et al.⁵ and Hashimoto et al.,² strengthening of the intrinsic muscles of the foot is possible with training programs designed specifically for these muscles. These strengthening programs have also shown positive effects on MLA height and shape,^{2,5} balance,⁵ and movement performance.² Multiple studies have also shown that strengthening these muscles is possible by running barefoot or in minimalist shoes.⁸⁻¹⁰ Proponents of barefoot running also believe that there is a decrease in injury due to the changes observed in the intrinsic foot musculature and the supposed increase in lower extremity postural control that accompanies these changes, however, the only quantitative evidence is from laboratory situations.¹¹

Studies involving other active populations, besides runners, are scarce. The knowledge of how training barefoot or shod affects foot muscle size and strength can be beneficial to other groups who are interested in preventing or treating lower extremity injuries and improving functional performance. The purpose of our study was to compare the intrinsic and extrinsic foot muscle size and strength in gymnasts (who predominantly train barefoot) and cheerleaders (who predominantly train shod). Another purpose was to compare time to stability (TTS) after a functional landing task between the normally shod and barefoot groups. The landing task was performed by both groups in both barefoot and shod conditions. MLA height was also measured and used for descriptive purposes.

We hypothesized that gymnasts would have larger foot muscles and greater toe flexor strength than cheerleaders. We also hypothesized that gymnasts would have shorter TTS than cheerleaders in both barefoot and shod conditions.

METHODS

This study was an observational study with a cross-over design for the test of TTS. We used Latin-square randomization, with participants drawing their treatment order from a bag. Inter-group comparisons were made with the independent variables being 1) gymnast or 2) cheerleader. The dependent variables were 1) foot muscle size, 2) toe flexor strength, and 3) TTS (balance). Descriptive variables included: age, height, weight, years of participation in gymnastics or cheerleading, training hours per week, and MLA height.

Participants

We recruited female gymnasts and cheerleaders ranging in age from 18–26 years (see Table 1). Each gymnast or cheerleader needed to be highly trained in her athletic event. She must have been training in either gymnastics or cheerleading for at least the last five years and could

not have participated in the contrasting activity during the previous five years of training. All subjects were required to be free of lower extremity injury or any injury that may have affected their balance (nerve injury, concussion, etc.).

If subjects met the above-mentioned inclusion criteria they were contacted to schedule their data collection session. Institutional Review Board approval was obtained, and each subject gave written informed consent before participation. Subjects filled out a questionnaire to obtain demographic information, which included her age, height, weight, the number of years she has participated in either gymnastics or cheer, average hours of training per week, and shoe type normally worn on a daily basis (see Table 1). Once informed consent was obtained and the demographic questionnaire was completed subjects were allowed to continue the data collection process.

Equipment

Ultrasound imaging was used to assess and collect foot muscle size data. Data was collected using a ML6-15 linear probe or a 9L linear probe (GE LogiqP6, General Electric Company, Fairfield, CT) depending on which muscle was being measured. Intrinsic foot muscle strength was measured using a custom strength dynamometer developed by our research lab using a ErgoPak force gauge (Hoggan Health, Salt Lake City, UT). The Arch Height Index Measurement System (AHIMS) was used to measure foot length, truncated foot length and dorsum height. Dynamic force plates (OR6 series, Advanced Mechanical Technology, Inc., Watertown, MA) were used to collect the ground reaction force data used to calculate TTS.

Testing Procedures

Subjects reported to the Human Performance Research Center on Brigham Young University Campus to receive instructions and have questions answered, read and sign the informed consent form, and to have measurements taken. All researchers taking measurements were blinded to whether the subject was a cheerleader or gymnast. The lead researcher issued each subject the demographic information questionnaire before any measurements were taken. Once the questionnaire was complete the participant was guided to the ultrasound imaging station.

Lower Leg Measurements. First, lower leg measurement sites were located using a tape measure to ensure that muscle measurements were taken at the correct, consistent locations. The lateral side of each leg was measured from the middle of the lateral knee joint line to the inferior aspect of the lateral malleolus. A mark was made on the skin 30% and 50% of the distance below the lateral knee joint line. The medial side of the leg was measured from the middle of the medial knee joint line down to the inferior aspect of the medial malleolus. A mark was made on the skin half way (50%) between those two locations.

Muscle Size Measurements. Next, the intrinsic and extrinsic muscles were measured using the following protocol adapted from the protocols previously used and shown reliable.^{12,13} Pictures depicting the probe placement for the muscle measurements are shown in Figure 1. First, the intrinsic muscles were measured. The navicular tuberosity was located and then the probe was moved inferior and lateral in the frontal plane on the plantar surface of the foot. The flexor digitorum brevis (FDB) was found in this area and resembled a pickle. Quadratus plantae (QP) was viewed and measured just below the FDB.

The abductor hallucis (ABDH) was the next muscle to be measured. The ABDH was located by moving the probe to the dorsum of the foot and then locating the navicular tuberosity. The ABDH was viewed and measured in this probe position.

The extrinsic muscles, fibularis brevis (FB) and fibularis longus (FL), were then measured. The probe was placed 50% of the way between the fibular head and the distal aspect of the lateral malleolus to measure the FB and 30% of the way between the fibular head and the distal aspect of the lateral malleolus for the FL measurement.

Finally, tibialis posterior (TP) was measured using the 9L probe. The TP was located on the lateral side of the lower leg and looked like a large block with the interosseous membrane running between it and tibialis anterior. It was insured that the interosseous membrane and lower border of the TP were visible in the image.

Arch Height Index Measurements. Once all ultrasound measurements were taken the subject was moved to the arch height measurement station. Bilateral arch height was measured while seated and in standing position with the AHIMS calipers (Figure 2) using the following protocol.¹⁴

First, the seated measurement was taken for the left MLA. The subject was seated with the left hip, knee, and ankle joints at 90°. One block was placed under the metatarsal heads and another block was placed under the heel of the left foot (block height = 4.5cm) leaving the MLA unsupported. The right foot was placed on a scale of equal height 15 cm medial to the left foot and moved posteriorly so that the distal end of the first ray of the left foot was 5cm behind the heel of the left foot. This allowed for easy maneuvering and viewing of the AHMIS calipers.

The AHMIS was then positioned with the heel cup against the heel of the left foot and horizontal sliding calipers were used to measure foot length (FL) and truncated foot length (TFL)

(distance from the heel to first metatarsal head). The vertical sliding caliper was then positioned at 50% of the FL, and then was used to measure the dorsum height (DH) (the height of the dorsal aspect of the foot from the floor at 50% of the FL). Arch height index was then calculated as the ratio DH/TFL . Steps 1–5 were repeated for the right MLA. Arch height measurement setup is shown in Figure 3.

Once bilateral arch measurements were taken in the seated position, the subject stood with their feet placed in the same positions on the blocks. They stood with 90% of their body weight distributed on the foot being measured,¹⁵ using the scale under the contralateral foot to measure their weight distribution. Both MLA heights were measured using steps 1–5.

Toe Flexor Strength Measurements. After arch height measurements were completed the subject moved to the toe flexor strength station. Bilateral toe flexor strength was measured with the custom strength dynamometer using the following protocol.¹⁶ The subject was seated with the knee flexed to 90°. An S-biner (see Figure 4) was attached to the dynamometer to test the strength of the first ray individually. A board the length of the subject's TFL was placed underneath the foot to allow room for MTP joint flexion. The subject was instructed to pull to maximal plateau for a count of 3 seconds and then instructed to relax at the end of the 3-second trial.

Steps 1–3 was repeated for the 2nd, 3rd and 4th rays combined. A metal bar held between the toes was used instead of the S-biner. Steps 1–4 were repeated for the contralateral foot. Each foot was tested 3 times.

Time to Stability Measurements. TTS was obtained by measuring ground reaction force (GRF) displacement for both static and dynamic conditions. Testing order was randomized for each subject. The possible test conditions were shod single-leg drop landing, shod double-leg

drop landing, barefoot single-leg drop landing, and barefoot double-leg drop landing. The following protocol was used:

Static Stability Measurements. Before the barefoot trials were performed each subject stood on both feet, looking straight ahead with her arms crossed across her chest. She held this position for 10 seconds until she was instructed to relax. Another 10-second trial was collected, but this time the subject stood only on her dominant leg. Before beginning the shod trials, a third 10-second trial was collected in the shod condition on only the dominant leg.

Dynamic Stability Measurements. Subjects were suspended above the force plates using gymnastic rings attached to a bar suspended from the biomechanics lab ceiling. A researcher assisted each subject when she jumped up to grab the rings and ensured she had a firm grip on the rings before stepping away. The subject was instructed to hang from the rings with her arms fully extended with relaxed shoulders to keep the drop height as consistent as possible. The height of the bar was adjusted for each subject, using a hand operated winch (see Figure 5), such that the sole of her heel (directly below the lateral malleolus) was 40 centimeters above the force plate.

Subjects were instructed to look straight ahead and to release their grip on the rings when instructed to drop without pulling themselves up or swinging before dropping. The research assistant running the Vicon system (VICON Nexus Software, VICON Motion Technologies, Centennial, CO, USA) gave instructions for each test trial. The subject was instructed to hang from the rings until the researcher gave the command to drop. The subject was instructed to land on the force plate in a position that was natural to them and to hold that position for 10 seconds where upon the researcher instructed them to relax. Each subject completed 3 satisfactory test

trials for each condition (12 trials total). The mean of the 3 trials for each condition (4 conditions total) were used for statistical analysis.

Discarded Trials. Test trials were discarded if any of the following situations occurred.

1) The subject lifted herself up or swung on the rings before letting go. 2) The opposite foot was used to restore balance during single-leg trials. 3) The subject stepped off of the force plate before the 10-second trial was complete. 4) The subject landed with part of the foot off of the force plate. 5) The subject landed with a portion of one foot on both force plates.

Data Processing

Two images were taken of each muscle (ABDH, FDB, QP, TP, FL, and FB) of the right and left limb. Each muscle measurement was outlined manually (see Figure 6) using internal software of the GE LogicP6 and then the two measurements were averaged.¹²

Toe flexor strength data were collected using a custom-made dynamometer and ErgoPak software (Hoggan Health Industries, Salt Lake City, UT). Three successful trials were recorded for the left great toe, the left lateral toes, the right great toe, and the right lateral toes (12 trials total). The strength data were imported into custom-made software using LabVIEW (National Instruments, Austin, TX). This software calculated the peak force of each trial and then exported the peak forces of each trial into an Excel spreadsheet. The 3 peak force measures for each condition were then averaged.

TTS data were calculated using GRFs collected using dynamic force plates that gathered data at a sampling rate of 1000 Hz using the Vicon system. A 10-second static trial was recorded in both double- and single-leg stances before drop landings were performed to establish a baseline measure of stability for each subject. Each subject performed 3 successful trials in each

condition (12 trials total). The mean of the 3 successful trials for each condition (4 total) was used for statistical analysis.

Following the processing of data in Vicon the successful double leg trials were transferred into Visual 3D Professional (C-Motion, Inc., Germantown, MD, USA) and processed to combine the forces of the two force plates. Once the double-leg trials were processed all successful trials were imported into custom-made software using LabVIEW (National Instruments, Austin, TX). This software analyzed and calculated the time at which a subject became stable using the sequential estimation technique discussed by Colby et al.¹⁷

Statistical Analysis

Univariate analysis was performed to determine if there were any significant differences between groups for the demographic data. Next, a mixed model analysis was performed to determine the significant covariates for each of the TTS conditions excluding sport. Finally, a regression analysis with a step-wise progression was run for each TTS condition using the appropriate covariates (see Table 2) and variable sport to determine if there were significant differences between groups. The alpha level was set at 0.05. SAS 9.4 (SAS Institute Inc, Cary, NC) was used for statistical analysis.

RESULTS

Subject demographic information is presented in Table 1. The average age, height, and weight were similar in both cheerleaders and gymnasts ($p > 0.05$). However, average weekly training hours differed significantly between cheerleaders and gymnasts, averaging 10 ± 3.7 hours and 21.6 ± 1.8 hours, respectively ($p < 0.001$). Training start age also differed significantly between cheerleaders and gymnasts averaging 11.6 ± 3.2 years and 5.2 ± 2.2 years, respectively ($p < 0.001$).

Fourteen out of 16 cheerleaders had neutral arch height indexes. One cheerleader's left arch height index was classified as low and another cheerleader's left arch height index was classified as high. Fifteen out of 16 gymnasts had neutral arch height indexes. One gymnast's arch height index was classified as high bilaterally.

Only one muscle, fibularis longus, was significantly larger in gymnasts than it was in cheerleaders (Table 3, $p = 0.017$). The mean muscle size for each muscle can be found in Table 3. No significant between-group differences were found for great toe flexor strength (Table 4, $p = 0.274$) or lateral toe flexor strength (Table 4, $p = 0.824$). There was also no significant difference between gymnasts' TTS and cheerleaders' TTS for any drop landing condition (Table 5, $p = 0.086 - p = 0.90$). Dominant and non-dominant arch height index did not differ significantly between groups (Table 6, $p = 0.671$ and $p = 0.608$).

DISCUSSION

The purpose of our study was to compare the intrinsic and extrinsic foot muscle size, toe flexor strength, and TTS following a drop landing between cheerleaders and gymnasts. Observing the differences in these dependent variables may help us further understand the effect training barefoot has on foot muscle size and strength and how this affects a functional task like balancing after a drop landing. Our data primarily did not support our hypothesis that gymnasts would have larger intrinsic and extrinsic foot muscles, greater toe strength, and shorter TTS than cheerleaders.

Between-group comparison of the mean muscle size for each muscle measured, corrected for body weight, showed that the only muscle that was significantly larger in gymnasts was the fibularis longus ($p = 0.017$), while the flexor digitorum brevis approached a significant difference ($p = 0.078$). Between-group comparison of great toe strength and lateral toe strength

did not show any significant differences. Additionally, there was not any significant between-group differences in TTS during any of the drop landing conditions.

It is possible that training stimulus plays a very large role in the adaptations of foot muscle size. Cheerleading and gymnastics are very similar activities, especially in regards to the lower extremity. Tumbling and balancing are large factors in both events. The athletes who participate in these activities are also quite similar in stature because of the close relationship between these sports. This was reflected in our subjects, where there were no significant between-group differences in height ($161.9 \pm 0.4\text{cm}$ vs. $159.3 \pm 4.9\text{cm}$) or weight ($58.7 \pm 7.1\text{kg}$ vs. $56.7 \pm 4.3\text{kg}$). The groups also had almost identical dominant foot length ($23.5 \pm 1.2\text{cm}$ vs. $23.3 \pm 0.9\text{cm}$). Having a very similar training stimuli for two groups, who are very similar in height, weight, and foot length, with the only major difference being that one group trains barefoot and one trains shod, likely did not produce a large enough difference in stress on the foot musculature to bring about the changes or adaptations evident in other barefoot populations.

Tumbling and landing on a spring floor or cushioned mat while barefoot may apply similar demands to the foot musculature as tumbling in a cushioned shoe. The cushioned mat may dampen the GRF, and therefore reduce the eccentric activation needed in the intrinsic foot muscles to absorb these forces. A study by Dixon et al.¹⁸ observed the GRF experienced by shod runners on different running surfaces, asphalt and a rubber-modified bituminous material. The study found a significant reduction in loading rate for the rubber-modified bituminous material compared to the asphalt ($p < .1$). Another study compared the landing peak GRF following a 46cm drop jump onto a 2cm thick aluminum plate and a 5cm thick closed cell wrestling mat.¹⁹ The GRF was significantly less for the mat landings compared to the aluminum landings ($p <$

.001). Both of these studies had the subjects wear shoes, but it is likely the findings extend to barefoot conditions as well.

The main actions of the FL muscle are plantarflexion and pronation of the subtalar joint. A study comparing the biomechanics of forefoot landings in barefoot and shod conditions found that barefoot subjects had significantly greater plantarflexion at toe contact.²⁰ De Wit et al.²¹ observed this same adaptation in barefoot runners and also noticed that this talocrural joint action happened in free-flight as a strategy to prepare for barefoot landing. They also correlated this onset of increased plantar flexion with lower peak heel pressures. Gymnasts, in an attempt to decrease the peak force on the heel upon landing, may plantarflex the ankle more than cheerleaders do in a shoe. This increased pre-activation of the plantarflexors (including FL) may contribute to the significantly larger FL size seen in gymnasts.

Pronation of the foot is another mechanism used to decrease the impact forces placed on the foot as it increases the time over which energy can be absorbed.²² Arampatzis et al.²³ studied the impact that drop height had on muscle activation and foot motion during landings. They discovered that FL activation was greatest during the landing phase of the highest drop landing and that the peak activation occurred around the same time that peak GRF occurred. It was speculated FL activation increases plantar flexion of the talocrural joint to help bring about pronation. The increased activation of FL and increased joint eversion caused by drop height influenced contact area and the amount of stress placed on the calcaneocuboid joint.²³ Increasing contact area provides a larger area to dissipate the GRFs experienced during landing. The increased activation of the FL in gymnasts in order to pronate the foot to guard against the GRF experienced in barefoot landings may contribute to the larger FL muscle size compared to cheerleaders.

Studies have shown pre-activation of the FL and tibialis anterior muscles prior to heel contact in running or landing from a fall.^{1,24-26} It is believed that this co-contraction of muscles helps provide dynamic stiffness to the joint to help resist moments applied to the joint during functional tasks.^{25,26} Pre-activation of the FL has been found to occur sooner and at a higher activation level in barefoot conditions.²⁷ During running there is an inversion moment at the subtalar joint at initial contact.²⁸ It is likely that there is an inversion moment at the initial contact during tumbling landings as well. The FL will eccentrically contract to limit inversion of the calcaneus as it is a primary everter of the subtalar joint. Scott et al.²⁷ studied the effect of footwear on lower leg muscle activation during walking and discovered that FL peak activation was lower while shod than barefoot. These researchers theorized that the construction of the shoe helped brace the foot and decreased the demand on the FL to control medial to lateral stability.²⁷ It is likely that the barefoot gymnasts have larger FL because they rely solely on muscle activation to provide ankle joint stiffness and to decelerate inversion of the calcaneus during landings.

Previous studies have shown increases in size of certain foot muscles following transition to minimalist shoe running. Two separate studies found increases in abductor hallucis CSA following transition to the five-finger Vibram minimalist shoe.^{8,9} Bruggemann et al. observed increases in the size of multiple extrinsic foot muscles following an intervention of performing running warm-up in Nike free minimalist shoes.²⁹ Bruggemann also observed a significant increase in MTP joint flexion strength. However, no studies have examined the differences in foot muscle size or toe flexor strength in cheerleaders and gymnasts.

One reason we may not have observed the same strength differences between gymnasts and cheerleaders that were evident in the minimalist shoe runners and traditional shoe runners is

that runners are subjected to MTP flexion at a higher frequency than gymnasts and cheerleaders are. Runners experience MTP flexion during the later stages of the stance phase of each stride.³⁰ Long and short MTP muscles are needed to help offset the dorsiflexion moment caused by GRF at the MTP.³¹ MTP flexion is also needed in gymnastics and cheerleading, but these activities have a much lower frequency of MTP flexion over the duration of the activity than running does.

Toe flexor strength has been found to be significantly correlated with intrinsic foot muscle CSA. Abe et al.³² discovered that FDB CSA is correlated with toe flexor strength in women ($p = 0.002$). Another study found that the CSA of FDB and QP (along with flexor hallucis brevis and the lumbricals) were both correlated with TFS ($p < 0.001$).³³ We did not find between-group differences in toe flexor strength, probably due to the fact that there were no significant differences in intrinsic foot muscle size between groups. The groups might have been too similar in regards to height, weight, and foot length, and the stress placed on the foot from their activities was too similar to bring about size or strength adaptations in the gymnasts different from the cheerleaders.

The strength testing method we used may also have impacted our findings. The custom-made dynamometer required the subjects to grip an S-biner (see Figure 4, A) with their great toe and a small metal bar (see Figure 4, B) with their lateral toes. We observed that many of the subjects were small in stature and had relatively short toes which caused difficulty in gripping the bar. The subjects may not have been able to give maximum effort during the strength testing because of poor grip on the bar. Another way we could have improved our strength testing would have been to add a measurement of inversion and eversion strength. The one muscle we found to be significantly larger in gymnasts is an everter of the subtalar joint so it was not involved in our

method of strength testing. It is likely we would have seen between-group differences in everter strength as increased muscle size is indicative of increased strength.³³

Studies comparing the TTS for two healthy populations, similar to our groups, are scarce. In contrast, multiple studies comparing an injured group (functional ankle instability, previous ACL injury, etc.) and control group exist. Two studies involving subjects with functional ankle instability found that those suffering from functional ankle instability took longer to become stable in the medial-lateral direction following a jump landing.^{34,35}

The drop landing task might not have been challenging enough for the healthy, highly trained subjects who participated in our study. The drop height of 40cm was selected because a previous study, that examined TTS between healthy subjects and those with functional ankle instability, found significant results.³⁴ In addition, we believed it was a safe height for collegiate athletes to drop from onto a hard surface and not impose increased risk of injury to our participants.

A greater height may have made it a more challenging task. However, Wenxin et al. found that TTS following a double-leg drop landing actually decreased as drop height increased.³⁶ The researchers observed larger joint angles at the knee and hip joint with increased drop heights and speculated that greater muscle activation throughout the entire lower leg may have been present with greater heights as subjects tried to protect themselves from the drop height thus reducing TTS. For our study we wanted to focus mainly on the intrinsic and extrinsic muscles of the foot so a greater drop height may have tainted our findings as muscles higher up the kinetic chain would have been activated at an even greater level.

One study, that required fatigued subjects to jump forward, found increased TTS in the anterior-posterior directions but not in the medial-lateral directions.³⁷ This suggests that the

nature of a task might affect the results. Our subjects fell directly down from a bar suspended over the force plates. Our TTS testing method may have been improved if we had the subjects perform jump landing tasks in the horizontal plane (lateral jumps and forward jumps). These tasks may have been more challenging for our subjects who are trained to make challenging landings while tumbling and may have made it possible to detect between-group differences in TTS.

Finally, the fact that 90.6% (29/32) of our subjects had neutral arch height ratios may explain why we did not see greater differences in TTS. Tsai et al.⁴ found significant differences in postural control, measured by center-of-pressure (COP) displacement, in subjects who had pronated feet and supinated feet compared to those with neutral feet. A similar study measured COP excursion area during 10-second single-legged static trials and found significant differences in excursion area between cavus feet and rectus feet.³⁸ Only three of our subjects were classified as either high-arched or low-arched by the AHMIS. These study results support the theory that because the majority of our subjects had similar arch heights there were not significant differences in TTS.

CONCLUSIONS

The findings of our study indicate that there were primarily no significant differences in the dependent variables between the two groups of interest. The only significant difference found was the larger fibularis longus in gymnasts compared to cheerleaders. We conclude that gymnasts training barefoot and cheerleaders training shod during their similar activities does not significantly affect intrinsic foot muscle size, toe flexor strength, or TTS in either barefoot or shod conditions between these two groups. The training stress placed on the gymnasts' bare feet on cushioned mats may be too similar to the stress placed on the feet of the shod cheerleaders. It

is likely that the similarities between height, weight, and foot length of our subjects also played a factor in the results found.

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Table 1. Subject demographic information

	Cheerleaders	Gymnasts	p-value
Number of Subjects	16	16	
Age (y)	20.4 ± 1.7	19.5 ± 1.1	0.095
Height (cm)	161.9 ± 5.4	159.3 ± 4.9	0.163
Weight (kg)	58.7 ± 7.1	56.7 ± 4.3	0.341
Average Practice Hours (weekly)	10 ± 3.7*	21.6 ± 1.8*	< 0.0001*
Training Start Age (y)	11.6 ± 3.2*	5.3 ± 2.2*	< 0.0001*
Dominant Foot Length (cm)	23.5 ± 1.2	23.3 ± 0.9	0.344
Number Right Leg Dominant	14	8	
Number Left Leg Dominant	2	8	
Two shoe types worn most often outside of activity	athletic sneakers, sandals	athletic sneakers, casual sneakers	

* Indicates significant difference between group means ($p < .05$)

Table 2. List of covariates used in regression analysis

Test Condition	Covariates used in regression analysis:
Barefoot Single Leg AP Force	Weight Dominant ABDH Sport
Barefoot Single-Leg ML Force	Weight Dominant TP Sport
Barefoot Double-Leg AP Force	Dominant TP Sport
Barefoot Double-Leg ML Force	Sport
Shod Single-Leg AP Force	Dominant AHI Dominant ABDH Sport
Shod Single-Leg ML Force	Dominant Lateral Toe Strength Dominant Great Toe Strength Sport
Shod Double-Leg AP Force	Dominant Lateral Toe Strength Dominant QP Sport
Shod Double-Leg ML Force	Sport

Table 3. Between-group comparison (mean \pm SD) of dominant leg intrinsic and extrinsic foot muscle size

	Cheerleaders	Gymnasts	p-value
Dominant ABDH	1.90 \pm .57	2.10 \pm .53	0.31
Dominant FDB	1.69 \pm .37	1.85 \pm .27	0.078
Dominant QP	1.68 \pm .45	1.64 \pm .30	0.78
Dominant TP	1.84 \pm .24	1.90 \pm .30	0.55
Dominant FL	4.18 \pm .83*	4.84 \pm 1.12*	0.017*
Dominant FB	3.33 \pm .63	3.52 \pm .74	0.46

* Indicates significant difference between group means ($p < .001$)

ABDH, FDB, QP, FL, and FB = cm^2

TP = cm

Table 4. Between-group comparison (mean \pm SD) of dominant great toe strength (kg) and dominant lateral toe strength (kg)

	Cheerleaders	Gymnasts	p-value
Dominant Great Toe Strength	4.28 \pm 1.33	5.11 \pm 3.42	0.72
Dominant Lateral Toe Strength	4.09 \pm 1.36	3.90 \pm 1.57	0.37

* Indicates significant difference between group means ($p < .05$)

Table 5. Between-group comparison (mean \pm SD) of time to stability (seconds) after double- and single-leg drop landings in barefoot and shod conditions

	Cheerleaders	Gymnasts	p-value
Barefoot Single-Leg AP Force	.61 \pm .16	.53 \pm .13	0.59
Barefoot Single-Leg ML Force	.35 \pm .10	.32 \pm .07	0.69
Barefoot Double-Leg AP Force	.66 \pm .12	.59 \pm .17	0.42
Barefoot Double-Leg ML Force	.37 \pm .09	.35 \pm .12	0.90
Shod Single-Leg AP Force	.58 \pm .30	.54 \pm .14	0.48
Shod Single-Leg ML Force	.47 \pm .44	.34 \pm .09	0.86
Shod Double-Leg AP Force	.73 \pm .21	.60 \pm .14	0.30
Shod Double-Leg ML Force	.43 \pm .40	.26 \pm .06	0.09

* Indicates significant difference between group means ($p < .05$)

AP = anterior-posterior

ML = medial-lateral

Table 6. Between-group comparison (mean \pm SD) of dominant and non-dominant arch height index (AHI)

	Cheerleaders	Gymnasts	p-value
Dominant AHI	.323 \pm .023	.321 \pm .022	0.67
Non-Dominant AHI	.318 \pm .022	.323 \pm .020	0.61

* Indicates significant differences between groups means ($p < .05$)

AHI = Dorsum Height \div Truncated Foot Length

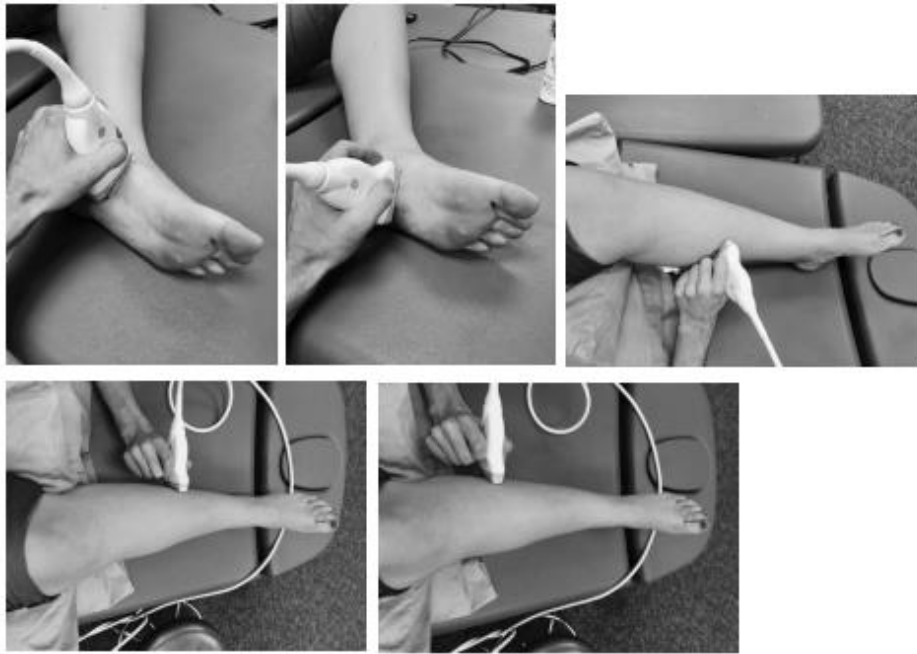


Figure 1. Probe placement for the measurement of a) abductor hallucis, b) flexor digitorum brevis and quadratus plantae, c) tibialis posterior, d) fibularis longus, and e) fibularis brevis.

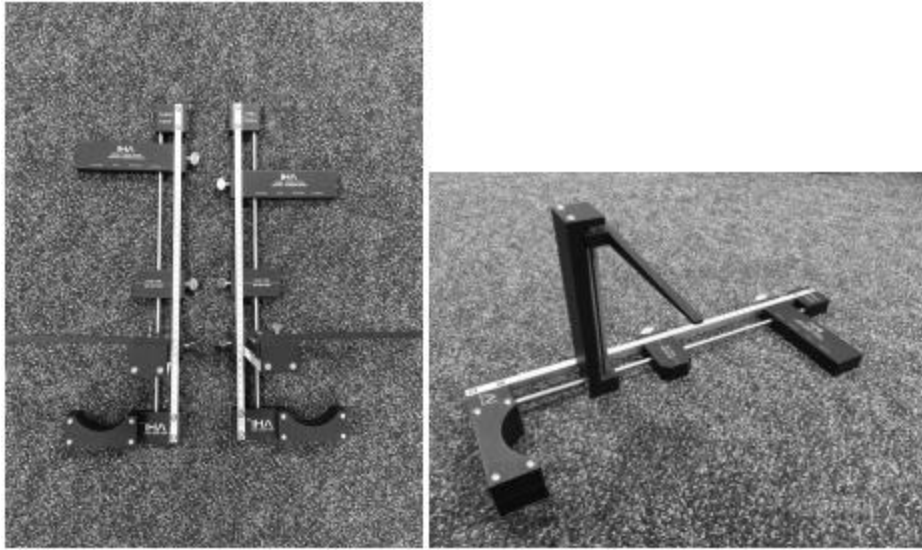


Figure 2. Arch Height Index Measurement System used to measure foot length, truncated foot length, and dorsum height for arch height index calculations.



Figure 3. Arch height index measurement setup.

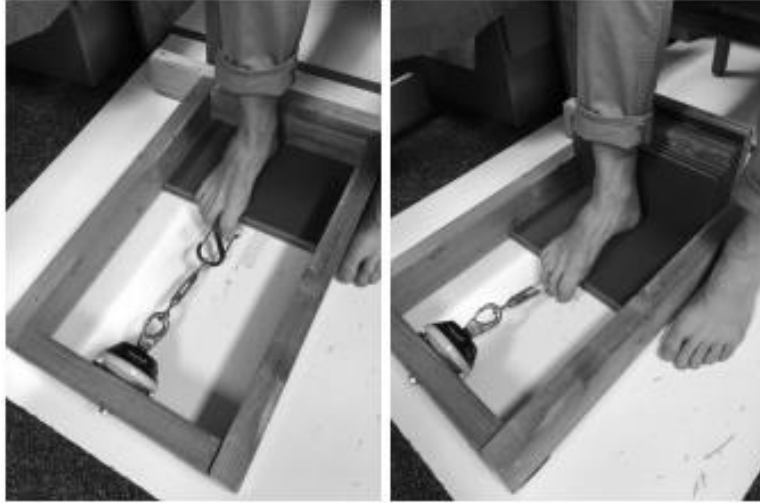


Figure 4. The custom made dynamometer used to test toe flexor strength. A) ErgoPak force gauge with S-biner (carabiner) used for great toe testing attached. B) ErgoPak force gauge with metal bar used for lateral toe testing attached. C) Strength testing station. D) Great toe strength testing. E) Lateral toe strength testing.

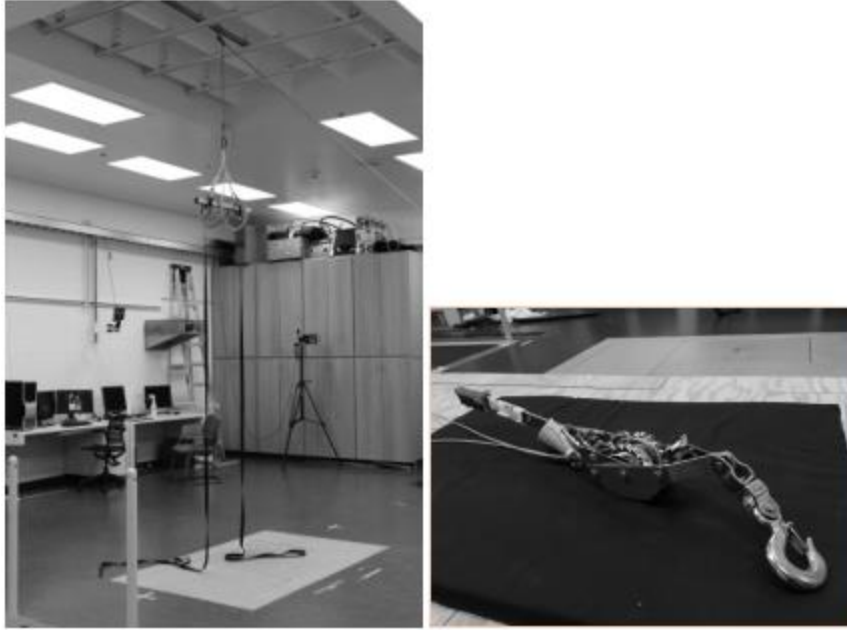


Figure 5. A) Suspension device above the force plates used to collect time to stability data. The subject held on to the wooden gymnastic rings and let go when instructed. Drop height was 40cm. The black ropes were used by research assistants to hold the subject steady while hanging. B) The hand operated winch was used to adjust the bar height for each subject.

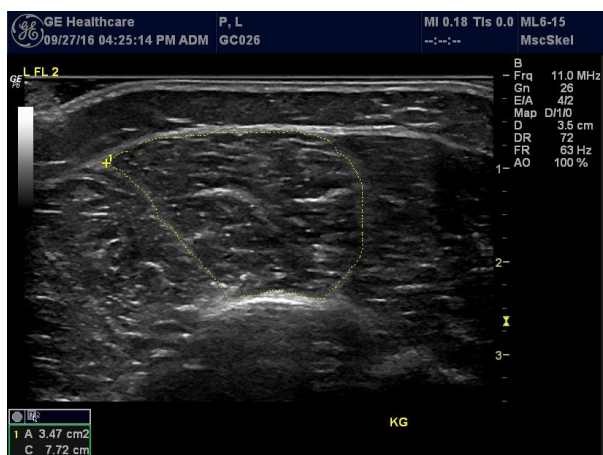


Figure 6. Outline of the cross-sectional area (CSA) of fibularis longus. The internal software of GE Logic was used.