The Effects of Passive Hallux Adduction on Posterior Tibial Artery Blood Flow Compared to the Lateral Plantar Artery

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The Effects of Passive Hallux Adduction on Posterior Tibial Artery Blood Flow Compared to the Lateral Plantar Artery

Jaysen Alani Hatch

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 Effects of Passive Hallux Adduction on Posterior Tibial Artery Blood Flow Compared to the Lateral Plantar Artery

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Master of Science

Passive hallux adduction has been shown to decrease blood flow in the lateral plantar artery (LPA) in a non-weight-bearing condition. Further research in weight-bearing and shod conditions is necessary to explore relationships between altered blood flow and injury or tissue healing. However, measuring blood flow in a shod foot would require an alternate measurement location to accommodate footwear, such as the more proximal posterior tibial artery (PTA).

PURPOSE: To determine changes in blood flow in the PTA and LPA subsequent to passive hallux adduction and to compare the observed changes between the two arteries. Second, to determine if measurement at the PTA is a viable surrogate for measurement at the LPA.

METHODS: Forty-one subjects (21 males, 20 females) participated in this study (age 23.5 ± 4.5 years, body mass 72.6 ± 13.7 kg, and height 173.1 ± 10.2 cm). PTA and LPA vessel diameter and velocity were measured via doppler ultrasound (L8-18i transducer GE Logiq S8). LPA was imaged distal to the abductor hallucis and the PTA posterior to the medial malleolus. Each artery was measured for 120 s: 60 s at rest followed by 60 s of passive hallux adduction. PTA and LPA metrics were log transformed and compared using a two-way repeated measures ANOVA, then the log transformed data was assessed with paired t-tests and Bland-Altman plots (alpha = 0.05).

RESULTS: There was an expected decrease in blood flow within each artery after passive hallux adduction (p < 0.001). The volume of blood flow differed between the arteries (p < .0001), but the change between baseline to first 5 cardiac cycles after hallux adduction was similar in each artery (p = 0.419). Bland-Altman analysis showed large spread limits of agreement, indicating the PTA underestimated or overestimated measurements at the LPA.

CONCLUSIONS: These data suggest that PTA blood flow behaves in a similar manner as LPA blood flow in consequence to passive hallux adduction. There is no significant difference in the absolute change of blood flow during hallux adduction between the LPA and PTA. However, Bland-Altman analysis suggests that the PTA is not a direct surrogate for the LPA due to the large variance in flow between the arteries. Despite this, the PTA can still be a beneficial location of measurement for plantar blood flow. Some reasons are that the PTA has a larger diameter making it an easier artery to image and allows for further research implications due to its ease of access in more applicable circumstances, such as in a shod condition.

Keywords: narrow shoes, footwear, compromised blood flow
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Introduction

Footwear serves important functions, such as protection and comfort of the foot, but is highly influenced by fashion and societal trends that often do not consider potentially harmful effects to the person and the foot. This is especially true in the design of women’s shoes (Menz & Morris, 2005). With so many different sizes, types, and designs of footwear, most adult men and women wear shoes that are too small for them, particularly with pointed toes and narrow toe boxes (Frey, Thompson, Smith, Sanders, & Horstman, 1993). However, a narrow forefoot toe box may predispose individuals for foot injury and pathologies, such as plantar fasciopathy, hallux valgus, corns, foot pain and hammer toes (Blanchard, Palestri, Guer, & Behr, 2018; Frey et al., 1993; Menz & Morris, 2005; Saxena & Fullem, 2004; Sobhani, Dekker, Postema, & Dijkstra, 2013).

Compromised tissue health and healing is highly associated with decreases in tissue perfusion. This is of concern within the foot due to its dependent position in the body and risk of pathology, such as diabetic foot ulceration, and to injuries, such as plantar fasciitis (Saxena & Fullem, 2004; Schwartz & Su, 2014). Appropriate healing of tissues needs a steady perfusion of oxygenated blood to the injury site (Whitney, 1990). An example of the foot with low perfusion and healing is the Achilles tendon, where lack of blood flow leads to tendinopathy and rupture (Ahmed, Lagopoulos, McConnell, Soames, & Sefton, 1998; Fenwick, Hazleman, & Riley, 2002). Further examples in the body where diminished blood flow and low tissue perfusion lead to delayed healing and nonunion fractures are the patella and scaphoid bones (Kawamura & Chung, 2008; Scapinelli, 1967). Additionally, the occurrence of ankle or foot injuries such as stress fractures and plantar fasciitis are prevalent with narrow toe box cleated sport shoes such as football and soccer (Jastifer et al., 2017; Mayer, Joyner, Almekinders, & Parekh, 2014) and may
be associated with poor blood flow and healing. Despite the many injuries that can happen with the foot, the blood flow to the tissues of the foot has been understudied.

A wide toe box may have advantages over a narrow toe box. Frey et al. suggest that a person’s forefoot would be better accommodated by a rounder, wider toe box than a narrower toe box shoe, however, limited research has been done to support this assertion (Frey et al., 1993). Use of a wider toe box shoe improved blood flow in the foot of individuals with diabetic foot ulcers (Crews, Smith, Ghazizadeh, Yalla, & Wu, 2017). In a recent study, it was reported that merely passively adducting the hallux resulted in a significant decrease in blood flow to the main artery supplying the plantar fascia (Jacobs et al., 2019). A similar hallux adduction likely occurs while wearing narrow and tight footwear. The effect of narrow shoes on plantar blood flow has yet to be considered in a society full of tight shoes.

Assessing blood flow to the foot presents challenges, especially in shod conditions. One study by Jacobs et al. utilized Doppler ultrasound to measure blood flow changes within an unshod non-weight-bearing foot (Jacobs et al., 2019). There was an initial decrease of 60% of blood flow in the lateral plantar artery (LPA) followed by a recovery in flow of about 30% over the span of 1 min, but a lasting decrease of at least 30% blood flow remains (Jacobs et al., 2019). However, using the methods established by Jacobs et al. is not feasible for measuring blood flow changes in the LPA while wearing footwear due to inaccessibility. To measure blood flow in a shod foot would require an alteration in measurement location, potentially proximally in the posterior tibial artery (PTA).

Replication of their method to induce adduction would allow a comparison of blood flow changes in both arteries (different locations). Measurement at the PTA proximal to its bifurcation
into the lateral and medial plantar arteries (Moore, 1992) should show a similar response and thus provide another measurement location to assess the response of blood flow to the foot.

Further research in weight-bearing and shod conditions is necessary to explore relationships between altered blood flow and injury or tissue healing. Therefore, it is important from both a research and clinical perspective to compare blood flow changes produced by passive hallux adduction in both the posterior tibial and lateral plantar arteries to determine if solely measuring at the PTA would provide the desired information.

The purposes of this study were: 1) to assess the changes in the blood flow within PTA subsequent to passive hallux adduction compared to the LPA, and 2) to compare via Bland-Altman analysis of PTA to LPA blood flow to determine if measurement at the PTA is a good surrogate for the LPA. This will be done by comparing blood flow responses during passive hallux adduction both distally (LPA) and proximally (PTA) to the site of artery compression between the abductor hallucis and the calcaneus.

Methods

Research Design

This was a crossover study with two conditions (resting foot and passive hallux adduction) measured at two locations (medial plantar aspect of the foot for the LPA and posterior medial malleolus for the PTA). The primary dependent variable was blood flow. The secondary descriptive variables were age, height, weight, lateral deviation angle of the hallux in a resting position, angle of the hallux during maximal adduction, arch height, and heart rate. Blood flow was measured in two conditions: resting hallux and adducted hallux. The descriptive variables were used to determine if there were significant covariates influencing the comparison between blood flow proximally at the PTA and distally at the LPA. In a pilot study, blood pressure was
found to not change with adduction of the hallux in a non-weight-bearing condition. Therefore, it was not measured in the current study.

Subjects

The participants for this study were adults over the age of 18 who were healthy and free of lower extremity injury (Female: \(n = 20\), Age: \(22 \pm 3.3\), Height: \(166.1 \pm 6.9\) Weight: \(65.6 \pm 11.0\); Male \(n = 21\), Age: \(25 \pm 5.0\), Height: \(179.8 \pm 8.1\), Weight: \(79.2 \pm 12.8\)). Subjects were excluded if they were currently suffering from plantar fasciitis or any other lower extremity injury, if they had any serious lower extremity injury within the past six months or if they had moderate to severe hallux valgus (measured at an angle of \(\geq 30\) degrees) (Garrow et al., 2001). Subjects were recruited from the campus of Brigham Young University and surrounding areas of Provo, Utah. Participants were recruited by word of mouth and by posting flyers around campus.

Power Analysis

A power analysis was performed comparing two means: 3.53 milliliters per minute and 1.36 milliliters per minute with a pooled standard deviation of 3.00 milliliters per minute based on previous pilot data. The analysis revealed that at least 31 participants were needed in order to detect significant differences using an alpha of 0.05. A second power analysis was performed to verify the first, using a mean of 1.51 milliliters per minute and a standard deviation of 0.62 milliliters per minute. The analysis revealed that at least 30 participants were needed in order to detect significant differences using an alpha of 0.05. We recruited a total of 45 subjects to prevent low power due to potential subject dropout. Four subjects had unusable data due to bad collection, imaging, or lack of data, so 41 subjects were used in the analysis.

Instruments

- Arch Height Index Measurement System (JAK Tool & Model, Matawan, NJ, USA)
- Dartfish Video Software (Fribourg, Switzerland)
- L8-18i-D, linear probe GE Logiq S8 with integrated ECG (General Electric Company, Fairfield, CT, USA)

**Procedures**

Individuals that were interested in participating in the study received an electronic copy of the study details prior to meeting with the primary investigator. The study details included inclusion and exclusion criteria and a description of what was required of the subject during the study. Since individuals with moderate to severe hallux valgus would be excluded, potential subjects were sent four images of varying levels of the pathology and asked to put themselves into a category as shown in Figure 1 (Garrow et al., 2001): between A and B, between B and C or between C and D. If the subject classified his or her right foot as a mild deformity or less (between A and B) and would like to participate, we scheduled a time to meet in the Mitchell and Johnson Orthopedic Rehabilitation Lab (292 SFH).

At this meeting, the subject was asked to read and sign an informed consent and was screened for hallux valgus. Subject was made aware of the hallux valgus requirements in the recruitment announcement and thus no study participant was excluded for this exclusion criteria. Once the paperwork was signed, we measured static arch height using the AHIMS device (Butler, Hillstrom, Song, Richards, & Davis, 2008). Arch height was measured in a seated position as the participant was in a non-weight-bearing position throughout each stage of the data collection process. The subject removed his or her shoes and was seated in a chair with the knees and ankles at approximately 90 degrees. The subject’s right foot was then placed in the AHIMS device. Sliding calipers were used to measure foot length, truncated foot length (length from
calcaneus to metatarsal heads) and dorsum height (measured at 50% foot length). The arch height index was then calculated by dividing dorsum height by truncated foot length.

Subjects were then asked about any exercise they had participated in that day and about any history of lower extremity injury. The subject’s height, weight and date of birth were measured and/or recorded. Additionally, photographs were taken of the subject’s feet, while seated, in order to measure the natural and maximal lateral deviation angle of the hallux. The natural deviation photo was taken of the relaxed foot from a superior view. For the maximal photo, an investigator passively adducted the hallux as far as it could be deviated without discomfort. Pressure was applied to the maximally adducted toe until there was blanching of the fingernail of the researcher. This photo was taken from the same superior view and from the same height each time.

The measurement location/artery order was randomized by having the subject draw the letter A or B from an envelope. If the subject picked the letter A, they started with the LPA and if they selected B then they started with the PTA. Next, the subject was asked to lay supine on a treatment table with a pillow under his or her right leg and the right hip slightly externally rotated. The subject rested in this position for 5 min in order to allow blood flow to normalize. No talking was permitted by the subject as it could disrupt and alter heart rate and blood flow. During this time, an alcohol wipe was used to clean the skin over the right and left chest, just inferior to the medial portion of the clavicle. A third site was cleaned over the lower right abdomen, just superior/anterior to the iliac crest. ECG electrodes were then adhered to the skin in these areas after the area. After the subject had been laying at rest for 5 min, ultrasound images were taken on the subject’s right foot by a certified vascular sonographer.
With the subject in the same supine position, an L8-18i-D linear probe was used to measure blood flow within the randomized chosen artery. If it was the LPA, the vessel was imaged just distal to the abductor hallucis muscle on the inferior medial side of the foot. If the PTA was chosen, the vessel was imaged proximally to the abductor hallucis muscle posterior of the medial malleolus. Sagittal and transverse images were taken under two conditions: resting and maximally adducted hallux. Sagittal images were taken in triplex mode, consisting of brightness (B-mode), color flow and pulse-wave modes. Transverse images were taken in B-mode.

First, while the participant was at rest a transverse video of the first artery was recorded for 60 s. After 60 s, the probe was turned 90 degrees, and a sagittal video of the vessel was recorded for 60 s. Once the video reached 60 s, the investigator passively adducted the hallux as far as it could be deviated without discomfort. This was done in the same manner as when measuring the maximal lateral deviation angle. The hallux was held in this position while the artery continued to be imaged in a sagittal view for another 60 s. After the 60 s of adduction, the hallux was released, and the subject laid at rest for 5 min to allow blood flow to normalize. Following the 5 min of rest, the hallux was again passively adducted to the maximal position, and a 60-s transverse ultrasound video was recorded. During each of these images the hallux adduction and natural angle was measured using Dartfish software from the same position as mentioned during history collection. Following another 5 min of rest to normalize blood flow, the second artery was imaged in the same manner. The subject was then dismissed and compensated $15 cash for his or her time.
Data Analysis

First, the photos were used to measure lateral deviation angles of the metatarsophalangeal joint. This was done using Dartfish software. The angle was lined up proximally along the first metatarsal and distally on the center of the toenail. The difference between the subject’s resting angle and maximal adduction angle was then calculated as shown in Figure 2.

Blood velocities were automatically computed from the sagittal view videos using Doppler technology. In pulse-wave mode, the ultrasound machine outputs an average blood velocity of the vessel for each cardiac cycle. The diameter was measured from the B-mode transverse images in order to ensure the true diameter was accounted for. The vessel diameter was measured from lumen to lumen within the artery. The integrated ECG data was used in order to allow for consistent measurement of vessel diameter throughout the cardiac cycle. Diameter was measured and recorded at end-diastole as represented by the peak of the R wave (Gifford & Richardson, 2017). Average blood velocity and vessel diameter were recorded for every cardiac cycle in the video, thus the number of measurements varied slightly among subjects based on heart rate. Blood velocity and vessel diameter were then entered into (1) in order to determine blood flow.

\[
\text{Blood Flow} = \text{Velocity}_{\text{mean}} \cdot \pi \cdot \left(\frac{\text{vessel diameter}}{2}\right)^2 \cdot 60
\]

Blood flow was recorded in milliliters per minute and was compared between resting and adducted conditions.

Pilot Study on Blood Pressure Effect

A pilot study was performed in which blood pressure was measured using photoplethysmography. Each subject was asked to lay in a supine position. A blood pressure cuff was fitted to the arm over the brachial artery. A finger cuff was then fitted to the third and fourth
fingers. Each of the subjects laid at rest for 5 min prior to any data being collected. Following the resting period, baseline mean arterial pressure was recorded. After the baseline measurement, the subject remained at rest for another 5 min after which blood pressure was measured for 60 s during maximal passive adduction of the hallux. The process was repeated three times. The results of the pilot study did not indicate a significant change in blood pressure between resting and adducted hallux positions.

**Statistical Analysis**

We first determined whether any descriptive variables acted as covariates with blood flow. To do this, we performed a stepwise regression analysis between blood flow and age, height, weight, biological sex, lateral deviation angle of the hallux in a resting position, angle of the hallux during maximal adduction, heart rate, and AHI. Next, based on Jacobs et al., blood flow was log transformed to account for large variations among subject responses (Jacobs et al., 2019). Changes in blood flow over the course of the 2-min trial were then analyzed using a two-way repeated measures ANCOVA, at two locations (PTA and LPA) and three time points: the average of 5 cardiac cycles before adduction (Baseline), the average of 5 cardiac cycles immediately after adduction is induced (Add5), and average of 5 cardiac cycles at the end of 60 s after adduction is induced (Add60). Post hoc testing (Tukey) was used in order to determine differences in blood flow among time points.

Bland-Altman (Earthman, 2015) analyses were performed to evaluate the agreement and bias between measurements at LPA and PTA. The change in blood flow between Baseline and Add5 in the LPA and PTA were calculated. The averages of the two differences were plotted on the x-axis ((ΔLPA + ΔPTA) / 2), while the difference of the changes in the LPA and PTA blood flow were then calculated and plotted on the y-axis (ΔLPA – ΔPTA) for each subject. Lines
representing two standard deviations were used to help visualize the magnitude of agreement between measures. Correlations were run on the values from the x-axis and y-axis. Bias, limits of agreement, and correlations were calculated to evaluate the difference in blood flow between Baseline and Add60. There are no specific guidelines on acceptable measures of variance, but it seems adequate to expect that the noise should not be greater than the signal or difference being measured. The average drop in log transformed LPA blood flow from Baseline to Add5 is 0.21 ml/min, so the range for the limits of agreement was set to be below 0.21 ml/min. The range of the Baseline to Add60 was set to 0.12 ml/min.

Finally, paired t-tests were used to verify that there were no differences in the adducted toe angle between transverse and longitudinal ultrasound trials.

**Results**

Sex was found to be a significant covariate in blood flow in the PTA (p = 0.009), and thus was included in the ANCOVA. The ANCOVA revealed a significant main effect of location on blood flow (p < .001), such that flow was generally higher in the PTA during all conditions as seen in Table 1 and Figures 3 and 4 (mean preadduction PTA blood flow: 8.1 ± 8.1 ml/min; mean preadduction LPA blood flow: 3.9 ± 10.1 ml/min). A main effect of time was also observed, such that adduction reduced blood flow in both arteries (p < .001; mean postadduction PTA blood flow: 7.2 ± 7.5 ml/min; mean postadduction LPA blood flow: 2.1 ± 4.6 ml/min).

Importantly, no interaction between location and time was observed, indicating that the change in blood flow elicited by adduction was not different between arteries (p = 0.419).

With no significant difference between the changes of log transformed blood flow in LPA and PTA, Bland-Altman analysis was executed to evaluate the agreement between these two measurements. The difference between the average change within each artery from Baseline...
to Add5 (Bias Add5) was −0.066 ml/min (2) and the difference between average changes from Baseline to Add60 (Bias Add60) was −0.088 ml/min (3).

\[
(\text{PTA Baseline} - \text{PTA Add5}) - (\text{LPA Baseline} - \text{LPA Add5}) = \text{Bias Add5} \\
(\text{PTA Baseline} - \text{PTA Add60}) - (\text{LPA Baseline} - \text{LPA Add60}) = \text{Bias Add60}
\]

The upper limit of agreement for Baseline to Add5 was 0.642 ml/min and the lower limit of agreement was −0.774 ml/min. The upper limit of agreement for Baseline to Add60 was 0.516 ml/min and the lower limit of agreement was −0.692 ml/min as seen in Figure 5. These limits exceeded the standard of 0.21 ml/min and 0.12 ml/min established a priori for an individual basis. Lastly, the correlations between LPA and PTA blood flow were: Baseline − Add5 $r = 0.09,$ $p = 0.249;$ Baseline − Add60 $r = -0.272,$ $p = 0.074.$

The difference in the induced adduction angle between the repeated trials was not significant ($p = 0.223$).

**Discussion**

The purposes of this study were to 1) assess and compare changes in blood flow within the PTA subsequent to passive hallux adduction to the response of the LPA and 2) determine if the PTA is a valid surrogate for measurement of plantar blood flow. Overall, the blood flow in the PTA decreased significantly following hallux adduction; a similar reduction was also seen in the LPA. Blood flow in the PTA was overall greater than that in the LPA. PTA and LPA blood flows did not differ significantly in their changes in blood flow reduction following hallux adduction at Add5 and Add60 from Baseline. Despite the measurements being moderately correlated, Bland-Altman analysis showed a large margin of error in estimating blood flow on an individual basis.
Posterior Tibial Artery Response

Passive hallux adduction had a significant effect on blood flow over time in the PTA. On average, there is a decrease in blood flow immediately following passive hallux adduction of $1.88 \pm 3.7 \text{ ml/min}$, but there was a recovery flow by the end of 60 cardiac cycles of adduction that exceeded the Baseline flow by $0.6 \pm 4.6 \text{ ml/min}$. It was expected that blood flow would have a recovery flow that would not exceed Baseline flow to give an overall decrease in blood flow with hallux adduction. This increase in blood flow may be affected by collateral blood flow pathways from the medial malleolar network (Ballmer, Hertel, Noetzli, & Masquelet, 1999) to assist in dispersing blood flow. It is important to also note the individual variation in blood flow between subjects, meaning that some participants likely had robust responses while others had a diminutive response. This is important to consider since the variation in blood response may be a factor in injury risk or healing rates.

Blood flow among the subjects varied greatly when measuring at the PTA. This individual variation necessitated an average be taken among the group to account for subjects with high blood flow rates compared to the study population. Despite seeing the expected outcome of decreased blood flow immediately following hallux adduction, there were some individuals who had an increase in blood flow compared to their Baseline. Among the group of subjects, some blood flow rates were drastically higher than the average during each of the three time points. For example, average blood flow Add60 was $8.4 \text{ ml/min}$, but some subjects were in the $20 \text{ ml/min}$ range, and in particular one participant had a blood flow measurement of $43.85 \text{ ml/min}$ that may have skewed the average data. Concurrently, other individuals showed minimal recovery in blood flow at Add60 compared to their Baseline. This vast variation in blood flow...
and blood flow recovery between individuals in PTA needs to be recognized, but it should also be noted that analogous variations were seen in the LPA measurements.

**PTA and LPA Comparisons**

The absolute volume of blood flow was different in the two arteries with the PTA having a larger flow volume. The larger flow volume is expected considering the PTA has a larger diameter and it supplies the LPA while also supplying other vessels. The vessels include the medial plantar artery and posterior medial malleolar branch of the PTA that connects to the medial malleolar complex (Ballmer et al., 1999). In comparing the changes of blood flow between the PTA and LPA at three time points over 2 min, as seen in Figures 2 and 3, we found that there were relatively similar reductions in absolute blood flow immediately after passive hallux adduction, as hypothesized.

This shows that the absolute change in blood flow from these time points was similar. Although these results showed similar responses, the absolute amount of blood flow differed between the arteries as well as the variation in the response to passive hallux adduction. In contrast to our hypothesis, in the Add60 blood flow measurement there was a greater recovery of blood flow within the PTA to exceed the Baseline flow as seen in Figure 4. There was an average decrease in blood flow from Baseline to Add60 in the LPA ($1.2 \pm 4.4$ ml/min, $p = 0.002$) compared to an increase in blood flow in the PTA to essentially equal the preadduction Baseline blood flow ($-0.6 \pm 4.6$ ml/min, $p = 0.27$). By log transforming the data to account for the large variation, we observed blood flow was no longer greater than Baseline, but almost equal to it in the PTA. (Average decrease in log transformed blood flow from Baseline to Add60. LPA: $0.12 \pm 0.23$ ml/min, $p = 0.01$; PTA: $0.03 \pm 0.15$ ml/min, $p = 0.006$)
A secondary purpose was to determine if the measurement of blood flow after hallux adduction at the PTA was a good surrogate for measurements taken at the LPA. Bland-Altman plots were used to analyze accuracy of the agreement between these two measurement locations. First, differences between the changes in the log transformed LPA and PTA from Baseline to Add5 and Add60 were $-0.066$ and $-0.088$ ml/min (y-axis). This shows that the PTA tends to underestimate differences in Baseline to Add5 and Baseline to Add60 in compared to the LPA as seen in Figure 5. Looking to the limits of agreement, we evaluated the magnitude of residuals on an individual basis. By looking at two standards of deviations, it is easily observed that these comparisons exceed our a priori established standard limit of agreement, meaning that similar measurements in the PTA to LPA could be due to error. This suggests that the PTA is not a good surrogate for LPA measurements. Correlations of Baseline to Add5 ($r = 0.085$, $p = 0.249$) and Add60 ($r = -0.272$, $p = 0.074$) show there is no significant correlation. The negative correlation found between Baseline and Add60 has been found due to the PTA blood flow recovering very quickly in a short span of time. It should also be noted that the correlation is weak enough that one or two subjects can switch the direction of the relationship.

Although the PTA may not be a great surrogate, the usefulness of measuring at the PTA needs to be considered for several reasons. The comparison of Baseline to Add60 may have not been significantly different between the two arteries, but Bland-Altman analyses suggest that the PTA is not an accurate surrogate for the LPA. Measuring at the PTA would not necessarily give the exact same results if measured at the LPA over the course of 60 s of adduction. However, we need to consider the fact that there is a greater chance of collateral blood flow to the PTA through vessels such as the posterior medial malleolar artery (Ballmer et al., 1999). Possibly if the foot were generally compressed, like being in a tight shoe, there would not have been as great
a recovery of blood flow within the PTA. It would be important to investigate the effect of overall foot compression on blood flow to and in the foot.

The PTA may provide a useful and viable assessment location for changes in blood flow to or within the foot. Jacobs et al. measured blood flow in the LPA and showed a significant decrease in blood flow as a direct result of tensing the abductor hallucis muscle through passive hallux adduction (Jacobs et al., 2019). We were able to show a similar response in both of the arteries we assessed. The LPA measurement location is along the medial, plantar border of the foot, deep to the abductor hallucis muscle in a supine, non-weight-bearing position (Jacobs et al., 2019). However, this measurement location (Figure 6) is not easily accessible when wearing shoes or standing in weight-bearing condition. In order to measure blood flow changes in the LPA while shod, the shoe would have to be altered (cut away) to allow access to the artery. This alteration of the shoe could potentially affect the measurement of blood flow in the LPA during a shod or weight-bearing condition. Measuring at the PTA instead of the LPA provides a second option for assessing blood flow changes within the foot that would not require any alteration of the footwear. Research designs that investigate a change within an individual between two experimental conditions could potentially use the PTA location and still draw useful conclusions.

Measuring at the PTA would be preferred for several reasons. Simply, the PTA has a larger diameter and is easier to image via ultrasound. Another reason would be the opportunity to further pursue research in this area under different shod conditions. Being able to assess blood flow across multiple types of footwear (i.e., cleats, high heels, minimalist shoes, etc.) would be beneficial in understanding the influence footwear types may have on blood flow within the foot. Doing so in a weight bearing condition would also increase application to daily living. Finally, a
shoe may alter not only toe alignment but also compression of vascular structures within the foot, leading to alterations in blood flow and compromised tissue health of the foot.

**Limitations**

This study has some limitations that may affect the observed results. The signal-to-noise ratio in measuring blood flow within these relatively small arteries was a potential limitation. The amount of blood flow within the PTA and especially in the LPA is significantly less than in larger arteries such as the femoral or brachial arteries. Thus, there is a great potential influence of measurement error when measuring blood flow changes in the smaller arteries. Due to variation among individuals, including levels of autonomic nervous control of blood vessels, there is normal and expected variation in blood flow leading to noise. Additionally, the PTA has potential for collateral blood flow via the medial malleolar complex that could affect the rate of recovery. This would vary between individuals based on their individual vascular branching anatomy including the branching of the LPA and medial plantar artery from the PTA. We accounted for this variation by taking averages over time and by having the same vascular certified sonographer perform all scanning. The sonographer imaged at the same marked location in order to minimize the effect of variable vascular branching.

Another limitation is that we measured at the two different arteries in different trials rather than during a single trial. This was due to having only one ultrasound probe. We assume that the observed effect would be similar in each trial. However, there may have been differences between trials, such as toe adduction angle or autonomic nervous response. To minimize this potential effect, trial order was randomized, and the same investigator applied hallux adduction with each subject. Lastly, imaging quality varied between subjects, making it difficult to image some diameters of vessels compared to others. Artery size may have been a factor in this as the
LPA is smaller compared to the PTA. Again, a single certified vascular sonographer performed all imaging scans to help minimize this influence of the smaller artery size.

**Conclusion and Clinical Application of Decreased Blood Flow**

Assessment of blood flow in the foot is important considering its influence on foot pathologies, injury incidence, and healing. Many foot pathologies are directly associated with compromised blood flow. Footwear may be a contributing factor to altered blood flow (Crews et al., 2017; Jacobs et al., 2019; Saxena & Fullem, 2004; Schwartz & Su, 2014) in a variety of shod conditions. Blood flow is important for proper and timely healing of tissues following injury or disease (Fenwick et al., 2002; Whitney, 1990). Many components in the blood initiate and complete the healing process, but when blood flow is slowed or halted, tissues have delayed healing times and can even experience cell death (Anitua, Andia, Ardanza, Nurden, & Nurden, 2004; Sen, 2009). Adequate blood flow is imperative for healing and a return to regular activities of daily living and an active lifestyle. For example, diabetes mellitus is highly associated with poor foot health due to vascular issues such as peripheral vascular disease and improper foot care (Edmonds, 2006; Faglia, Clerici, Caminiti, Vincenzo, & Cetta, 2013; Somroo, Hashmi, Iqbal, & Ghori, 2011; Tudhope, 2008). Another pathology that may be attributed to lack of blood flow is plantar fasciitis (Schwartz & Su, 2014). Plantar fasciitis has been found to be more of a cell death rather than inflammation and the most common source of heel pain (Schwartz & Su, 2014). These pathologies are routinely seen clinically, so considerations of blood flow perfusion need to be addressed during the healing process for pathologies of the foot. Measurement of blood flow within various shod conditions is of importance to better understand normal and altered blood flow patterns and the relationship between blood flow and pathology, injury, and
healing. Being able to assess the blood flow through the arteries supplying the foot, such as the PTA, may help overcome this information deficit.


Table 1. Lateral plantar artery (LPA) and posterior tibial artery (PTA) blood flow for average flow prior and during passive hallux adduction and the average blood flow at three specific time points and the change in blood from Baseline to Add5 and Baseline to Add60.

<table>
<thead>
<tr>
<th></th>
<th>Average Preadduction Blood Flow (60 s) (ml/min)</th>
<th>Average Adduction Blood Flow (60 s) (ml/min)</th>
<th>Baseline Average Blood Flow (5 cardiac cycles) (ml/min)</th>
<th>Add5 Blood Flow (5 cardiac cycles) (ml/min)</th>
<th>Add60 Blood Flow (5 cardiac cycles) (ml/min)</th>
<th>Difference Baseline to Add5 Blood Flow (ml/min)</th>
<th>Difference Baseline to Add60 Blood Flow (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPA</td>
<td>3.9 ± 10.1‡</td>
<td>2.1 ± 4.6‡</td>
<td>4.1 ± 12.2‡</td>
<td>1.4 ± 2.5‡</td>
<td>2.9 ± 8.4‡</td>
<td>2.6 ± 10.4*</td>
<td>1.2 ± 4.4†</td>
</tr>
<tr>
<td>PTA</td>
<td>8.1 ± 8.1</td>
<td>7.2 ± 7.5</td>
<td>7.9 ± 6.9</td>
<td>5.9 ± 5.9</td>
<td>8.4 ± 9.5</td>
<td>1.9 ± 3.7*</td>
<td>−0.6 ± 4.6</td>
</tr>
</tbody>
</table>

*Significant difference within artery change blood flow from Baseline to Add5 p < 0.001
†Significant difference within artery blood flow from Baseline to Add60 p = 0.002
‡Significant difference in total blood flow between the two arteries
Figure 1. Hallux Valgus Manchester Grading Scale. A) Grade 1 (no deformity), B) Grade 2 (mild deformity), C) Grade 3 (moderate deformity), D) Grade 4 (severe deformity). (Garrow et al., 2001)
Figure 2. Dartfish Photograph Analysis. Photographs of each subject’s foot were taken at rest and during both of the adducted hallux phases of the ultrasound protocol. First metatarsophalangeal joint angles were then measured using Dartfish software. (Jacobs et al., 2019)
Figure 3. Cardiac Cycle Representation of Blood Flow in the LPA vs PTA. Graph of lateral plantar artery (LPA) and posterior tibial artery (PTA) average blood flow at each cardiac cycle over 120 cycles, approximately 2 min. Red dotted line signifies the point of passive hallux adduction. Second graph is of the same data log transformed.
Figure 4. PTA vs LPA at Three Main Time Points: Baseline, Add5, and Add60. Graphical representation of the relative changes in blood flow due to passive hallux adduction at three time points for each artery. Baseline: average 5 cardiac cycles before adduction; Add5: average 5 cycles after adduction is induced; Add60: average 5 cycles at end of adduction. Standard error bars are represented. This was also done for the same data log transformed.
Figure 5. Log Transformed Bland-Altman Plots to demonstrate the accuracy of PTA blood flow estimating LPA blood flow with passive hallux adduction. A) Log Transformed Bland-Altman plot for ΔPTA – ΔLPA (Baseline – Add5) and B) ΔPTA – ΔLPA (Baseline – Add60). The Bias is represented by the solid black line and the dashed lines represent limits of agreement.
Figure 6. LPA and PTA Probe Placement with Placement at PTA in a Shod Condition. Representation of probe placement at the 1. LPA, 2. PTA, 3. PTA in shod condition.