Effects of habitual physical activity on foot strength and longitudinal arch stiffness.

CHLOÉ LAUER[1]

[1]**Department of Anthropology, University of New Mexico**

Abstract

Many people in post-industrial societies have weaker foot muscles and lower foot arch stiffness. The most common explanation for this phenomenon relates to footwear. We propose a different hypothesis: risk of developing weak, pliable feet may be related to the increasingly sedentary lifestyles in post-industrial societies. We hypothesize that people who do not use their feet much for physical activity are less likely to develop strong, stiff feet. We collected data on physical activity levels and foot strength and stiffness among a sample of adults in the United States who normally wear restrictive footwear. We measured daily step counts and time spent in moderate-to-vigorous physical activities, cross-sectional areas of foot muscles, longitudinal arch height and stiffness, and dynamic longitudinal arch stiffness during walking. Our results suggest that physical activity levels are not significantly associated with foot strength or stiffness, highlighting the key role of footwear in foot strength and stiffness.

Keywords: Longitudinal Arch, Physical Activity, Foot Strength, Foot Stiffness, Muscle, Minimal-shoes, Human.

The human foot is unique. It is drastically different than even our closest relatives, the apes (Harcourt-Smith & Aiello 2004:406). The morphological evolution of the foot seems to be beneficial for economical bipedal walking. In other words, the foot morphology of modern humans enables them to save energy when producing bipedal walking (Hu et al. 2021:8). The longitudinal arch present in the human foot is one of its key distinctive features. The abductor hallucis, the flexor digitorum brevis and the abductor digit minimi, three intrinsic muscles of the foot, are thought to have an important role in the support of the longitudinal arch. The longitudinal arch isn’t acquired at birth; rather, it develops through childhood (Wang et al. 2022:352). Since the longitudinal arch matures through childhood, one may wonder whether different environmental conditions might yield different longitudinal arch morphology or stiffness. Flat feet occur when the longitudinal arch collapses. The flat foot condition seems to have multiple origins. In some individuals, the longitudinal arch never develops. Flat feet can also be acquired as an adult and is usually thought to be the result of injuries or weakened feet (Staff 2021). It is estimated that about 20 to 25% of adults in the United States and Canada suffer from the flat foot condition (Gross et al. 2011:939).

Many studies have indicated that the rates of the flat foot condition in non-industrialized countries was significantly smaller than in developed/industrialized countries. This phenomenon has been linked to the wear of minimal shoes. In industrialized countries, individuals tend to wear conventional shoes which provide support for the longitudinal arch. On the other hand, minimal shoes or barefoot walking provides little to no support. To produce efficient bipedal walking, one must activate their muscles and stiffen their arches. An Indian study has found that individuals who didn’t wear shoes before their 16th birthday were two times less likely to develop flat feet (Sachithanandam & Joseph 1995:255). These data seem to indicate flat footedness being a mismatch disease. Conventional shoes might provide too much support and in doing so, inhibit the action and development of the intrinsic foot muscles and the longitudinal arch. Because shoes were nonexistent or in minimal forms for most of hominin’s evolutionary history, humans might not be adapted to wear them.

A recent study investigated the effects of shoes on foot strength and longitudinal arch stiffness (Holowka et al. 2018:1). In this study, the investigators assessed the foot strength and longitudinal arch stiffness of minimally shod population (here the Tarahumara) in comparison to conventionally shod populations. It was found that minimally shod populations have higher and stiffer longitudinal arch stiffness and larger intrinsic foot muscles than conventionally shod populations. This study concluded that flat foot condition might be a mismatch disease resulting from the use of comfortable and supporting shoes (Holowka et al. 2018:10). However, this specific study design didn't allow the investigators to control for physical activity. Indeed, the Tarahumara as a whole population are on average more physically active than an average conventionally shod American. One can thus wonder if and to what extend physical activity might be a confounding variable. In this case, physical activity rather than shoe wear might explain differences in prevalence of flat feet between industrialized and non-industrialized populations.

Physical activity in relation to foot strength is an emerging field of interest. Physical activity has been found to improve foot structure and function in obese population (Zhao et al. 2018:878). Foot muscle volume has also been seen to increase with foot strengthening program. This specific study investigated foot strength in relation to running performances (Taddei et al. 2020:113). Daily physical activity has also been seen to improve foot strength when wearing minimal shoes which provide little to no support (Curtis et al. 2021:7). Another study compared lifesaver athletes and “normal” individuals and found that lifesaver athletes possessed higher arches and more developed intrinsic foot muscles. They attributed this difference to physical activity on sand (Ichikawa et al. 2021:9).

Physical activity and foot strength are often studied in relation to other variables. There is little evidence in the scientific literature for the sole effect of physical activity on foot strength and longitudinal arch stiffness. The lack of targeted research on the relationship between foot strength and physical activity inspired the research question: What are the effects of physical activity on foot strength and longitudinal arch stiffness? This study hypothesizes that individuals with higher levels of physical activity have better foot strength and stiffer longitudinal arches than individuals with lower levels of physical activity. To assess this hypothesis, physical activity levels are recorded among a large sample with different physical activity levels. In this study, we predict that physical activity will be positively correlated with intrinsic muscle size. We also predict that physical activity will be positively correlated with longitudinal arch stiffness.

Materials/ methods

Sample. Data were collected for a sample of 40 participants (Mean ± SD: age, 26 ± 9 yrs; body weight, 75 ± 18 kg; height, 175 ± 11 cm). The participants are mainly recruited from UNM. No age limit or other demographic constraints restricted recruitments. Exclusion criteria however included foot pain, injuries to the foot, or any abnormality with the foot or the limbs that would impact physical activity levels. All levels of physical activity are desired. The recruitments process is done randomly. Participants are recruited through posts on social media, emails sent out to the anthropology undergrad list and flyers on the UNM campus.

All participants provided written consent after careful explanation of the research and its purpose. The study was approved by the University of New Mexico Institutional Review Board. The research follows the procedure outlined in the accepted proposal.

Accelerometer. Physical activity was recorded using accelerometers. The accelerometer used in this study is the Axivity AX3. This device records acceleration, or the change in velocity of an object over time. The accelerometer was placed on the left wrist as a bracelet to measure average daily step counts and average daily time spent in moderate-to-vigorous physical activity (MVPA). The bracelet was positioned in such way that the arrow inside of the bracelet would point at the body when on the wrist (Figure 1). The bracelet was put on the wrist following the mounting convention of the AX3 user guide. The bracelet was kept on the wrist for two weeks. The data from the accelerometers were collected using the Open Movement application. The accelerometer was set on the following settings: the frequency was set on a 100 Hz. The range was set on 8g. The recording time was set on Immediately on Disconnect. Other settings were left blank. The recording session ID number corresponds to the ID number of the participant.

Lab procedure. Participants came into the lab to have measurements taken on their feet. The data were collected in the following order. Anthropometrics data were gathered. An ultrasound was performed on the right foot. Participants walked on a treadmill and a force plate which recorded the ground reaction forces applied by their right foot. Go Pro camera captured videos of the treadmill walk. Photos of the foot were taken while sitting and standing.

Anthropometrics. Participants weight and height were measured in kilograms and centimeters. The weight was measured using a standard Taylor scale. The height was measured using a stick on the wall measuring tape. Height and weight were measured to calculate Body Mass Index (BMI) with the formula:

$$BMI = body\ mass/height^2.$$

The foot length was measured in centimeters using a foot caliper. The distance from the hip bone, or greater trochanter, to the ground (hip height or trochanter height) was also measured in centimeters. The right hip height was measured in centimeters. These measurements were used in the analysis of kinematic and kinetic data.

Ultrasound. The ultrasound is performed on the right foot of participants. The cross-sectional areas of the abductor hallucis, flexor digitorum brevis, and abductor digiti minimi were captured using a Philips L12-4 B-Mode Ultrasound Transducer (Philips Ultrasound, Inc., Bothell, WA) with a 4–12 MHz frequency range and a 41 mm linear array. The images were captured on a Samsung Tablet Galaxy Tab S7 using the Lumify application. The Lumify application was used with the following settings. MI: 0.9; TIB: 0.1; Frame Rate: 30Hz; 2D Gain: 50; Depth: 3.5cm; Transducer: L12-4; Preset: MSK; Power: -0.3dB. The ultrasound was performed by a single investigator to avoid instrumentation threats. The navicular tuberosity was taken has a point of reference for the ultrasound. The ultrasound was performed on a line starting from the navicular perpendicular to the foot.

The images from the ultrasound were used to calculate the cross-sectional areas of the abductor hallucis (AH), the flexor digitorum brevis (FDB) and the abductor digiti minimi (ADM) (Figure 2). AH and FDB are thought to have a crucial role in stiffening the LA during locomotion. ADM was included because it has been found its size increases in runners wearing minimal shoes. When the images didn't show clear muscle boundaries they weren't included in the analysis. Assuming that (body mass) is proportional to cross-sectional area, cross-sectional area was divided by (body weight) $^{0.67}$ for purpose of scaling (Holowka et al. 2018:3-4).

Walking task. Participants walked on a track composed by two wood parts (4m x 1m) and a AMTI force plate used to record ground reaction forces while walking (Figure 3). Participants were recorded by 2 8Black Go Pro video cameras labeled 1 and 2. Gro Pro 1 was used to record a medial view of the right foot and was placed 22cm from the force plate and at a 10cm height. Go Pro 1 recorded under the following settings: Standard 1080-120-L (video). Go Pro 2 was used to record a lateral view of the right foot and was placed 2.5m from the force plate at a 72cm height. Go Pro 2 recorded using the following settings: Standard 2.7k-60-L (video). The video was started by the investigator who gave green light for the participant to start walking. The video was ended when the participant got off the track.

Before recording, markers (small, circular white tape) were placed on the participants' right foot and hip. Markers were placed on the following locations: head of the first metatarsal, navicular tuberosity, medial malleolus, heel, proximal shank, and hip bone (Figure 4). Participants were asked to walk barefoot. Participants were asked to walk with a normal comfortable gait and to have their right foot only touch the force plate. Participants performed this task three times.

The lateral camera videos were used to calculate walking speed using ImageJ. The distance traveled by the greater trochanter was measured through multiple strides. By dividing this distance by the time it took to travel, we measured walking speed.

ImageJ was used to calculate mid-stance dynamic LA stiffness (k_{mid}). k_{mid} was calculated using the following formula:

$$kmid = \frac{Fmid}{\Delta LA\ height}$$

F_{mid}, was measured with the force plate. It is the vertical ground reaction force exercised by the foot at 50% of stance phase. $\Delta LA\ height$was calculated as the difference between LA height at touchdown and LA height at 50% of the stance phase. LA height was measured as the distance between the line passing through the calcaneus and the first metatarsal markers, and the navicular tuberosity marker. 50% of stance phase was taken as a point of reference because it corresponds to a time where ground reaction force vector is about perpendicular to the ground. It is also convenient because at that point the foot is almost entirely in contact with the ground, making the linear dimension in which LA height is measured perpendicular to the ground and the ground reaction vector as well. Because of these precautions, the change in LA-stiffness at midstance is thought to reflect changes in vertical ground reaction forces only. Thus, k_{mid} is assumed to represent relative LA stiffness.

Under the assumption that k_{mid} scales geometrically, it was divided by $(body\ weight)^{0.67}$ (Holowka et al. 2018:4-5).

Foot photos procedure. Photographs of the right foot were taken from the medial view (Figure 5). The photographs were taken with a 8Black Go Pro labeled 3. Go Pro 3 captured photographs under the narrow photo setting. Go Pro 3 was placed at a distance that remain the same through the different photographs. The right foot (still with the white markers) was photographed. The right foot was placed on two blocks of wood (15cm x 15cm) with the foot arch in between the two blocks. A scale was placed on the block supporting the toes.

Two photographs were taken with the participant sitting on a chair. Under this condition the participant exerts no load on the right foot. Two photographs were also taken with the participant standing up. Under this condition, the participant exerts maximum loading on the right foot. A black measuring tape was placed on the floor to indicate the standing position.

These photographs were used to calculate the Arch Height Index (AHI). AHI is calculated using the standing pictures. The AHI is calculated by dividing the foot's dorsum height at 50% of the foot length by the total foot length excluding the toes when participants are standing. The Arch Height Index is a reliable measure of the Longitudinal Arch (Holowka et al. 2018:3).

The Static Arch Stiffness (SAS) was calculated according to the following formula (Holowka et al. 2018:3):

$$SAS = \frac{(body\ mass * 0.4)}{(AHIseated - AHIstanding)}$$

In this case AHI is calculated in both seated and standing position. The procedure for calculating AHI on standing images is thus repeated on the sitting images.

Statistical Analysis

General linear models (GLMs) were used to test for associations between physical activity measures (step counts, MVPA) and foot strength and stiffness variables (muscle cross-sectional areas, LA height and stiffness), controlling for gender, age, and other variables. Analyses were conducted in JMP software and statistical significance was judged using $p<0.05$.

Results

Muscle Cross-Sectional Areas and Physical Activity. The association between the abductor hallucis, the flexor digitorum brevis and the abductor digiti minimi sizes and average daily step count was calculated using GLMs. It was found that all tests showed $p>0.2$, clearly showing no association between any of the muscle sizes and average daily step count (Figure 6).

In the same way, abductor hallucis, flexor digitorum brevis and abductor digiti minimi sizes were not associated to average daily minutes of moderate to vigorous physical activity with once again $p>0.2$ for all tests using GLMs.

Longitudinal Arch and Physical Activity. No significant association was found between foot stiffness and daily levels of physical activity using GLMs (Figure 7). GLMs were used to look at the association between three variables: arche height index (AHI), static arch stiffness index (ASI), and dynamic arch stiffness index (DASI), and two independent variables: average daily step count and average daily minutes of moderate to vigorous physical activity (MVPA).

Neither average daily MVPA time nor average daily step count were significantly associated with AHI with respectively $p=0.67$ and $p=0.88$. In this two test, age, gender, and body mass index were controlled for.

Average daily step count was not significantly associated with ASI with p=0.17. However, average daily MVPA time was significantly negatively correlated to ASI with p=0.03. In both tests, age and gender were controlled for.

Average daily MVPA time as well as average daily step count were not significantly associated with DASI with respectively, p=0.23 and p=0.58. In both tests, age, gender, and voluntary walking speed were controlled for.

Discussion

This study compared foot muscles size and biomechanics across a group of individuals with diverse levels of physical activity while controlling for age, gender and body mass index to test the hypothesis that lower level of physical activity would yield weaker more pliable feet. This hypothesis was not supported by the findings. We found that neither AHI nor DASI were significantly correlated to either daily step count or daily amount in minutes of medium to vigorous physical activity. ASI was negatively correlated to daily amount of MVPA however, no significant association was found with daily step count. Likewise, cross-sectional areas of the abductor hallucis, the flexor digitorum brevis and the abductor digiti minimi weren’t correlated to daily step count or daily amount in minutes of MVPA.

These results, although surprising, seem to indicate a nonexistent role of physical activity in foot strength and longitudinal arch stiffness. However, previous literature indicated that minimally shod populations had higher foot strength and stiffer longitudinal arches (Holowka et al. 2018:10). From that, it was proposed that flat feet were a product of an environment in which conventional shoes provide too much support, thus weakening the longitudinal arch and foot muscles (Holowka et al. 2018:10). Because flat feet are highly prevalent in industrialized societies, this hypothesis made sense. Industrialized societies are also more sedentary. Because this study investigated the effects of physical activity, we can assume that the differences observed between minimally shod versus conventionally shod populations in terms of foot strength and LA stiffness cannot be attributed to differences in physical activity levels. In this case, shoe wear provides a better explanation than physical activity for differences observed between minimally vs conventionally shod populations.

This study however possesses limitations. Physical activity was measured on a 10-day scale which constitutes a snapshot in an individual's life. Although this method is highly reliable to infer physical activity at a given moment, it doesn't reflect physical activity performed throughout life. This issue might introduce bias in the sample by assigning people high level of physical activity when in fact they weren't as physically active throughout the rest of their life. Moreover, if physical activity plays an important role in the development of the longitudinal arch, this would not be accounted for in this study. The lack of literature on the role of physical activity during the development of the longitudinal arch is concerning and need to be addressed to fully comprehend the flat foot condition.

Another limitation of this study produced interesting thoughts. It seems like the sample used is pretty active by USA standards, or any industrialized country for that matter. Indeed, American have an average of 3,000 to 4,000 daily steps (Rieck 2020). In the sample of this study, all subjects had an average daily step count over 5,800. Thus, the absence of correlation between foot strength and longitudinal arch stiffness and physical activity might be the result of a non-linear or threshold effect. Passed a certain, moderately high amount of physical activity, the results indicate non-restricted anatomical outcomes. People not meeting that threshold might on the other hand exhibit weaker feet and collapsed arches. This specific question deserves to be looked into and might be a good target for expansion of this research.

Conclusion.

The results of this study do not support the hypothesis that individuals with higher levels of physical activity have higher foot strength and stiffer longitudinal arches. No significant association between physical activity and foot strength and longitudinal arch stiffness among individuals with above average physical activity levels in restrictive shoe-wear was found. These results seem to be consistent with the hypothesis that individuals who wear minimal shoes have stiffer LAs (Holowka et al. 2018:10). Further research is necessary to investigate the effects of physical activity on longitudinal arch stiffness among populations with lower physical activity levels and among populations with minimal footwear. Future research should also tackle the medical implication of footwear and physical activity in the development of flat feet.

References

Curtis, R., Willems, C., Paoletti, P., & D’Aoû t, K. (2021). Daily activity in minimal footwear increases foot strength. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-98070-0

D’AoÛt, K., Pataky, T. C., De Clercq, D., & Aerts, P. (2009). The effects of habitual footwear use: Foot shape and function in native Barefoot Walkers†. *Footwear Science, 1*(2), 81–94. https://doi.org/10.1080/19424280903386411

Gross, K. D., Felson, D. T., Niu, J., Hunter, D. J., Guermazi, A., Roemer, F. W., Dufour, A. B., Gensure, R. H., & Hannan, M. T. (2011). Association of Flat Feet with knee pain and cartilage damage in older adults. *Arthritis Care & Research*, *63*(7), 937–944. https://doi.org/10.1002/acr.20431

Harcourt-Smith, W. E., & Aiello, L. C. (2004). Fossils, feet and the evolution of human bipedal locomotion. *Journal of Anatomy*, *204*(5), 403–416. https://doi.org/10.1111/j.0021-8782.2004.00296.x

Holowka, N. B., Wallace, I. J., & Lieberman, D. E. (2018). Foot strength and stiffness are related to footwear use in a comparison of minimally- vs. conventionally-shod populations. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-21916-7

Hu, D., Xiong, C.-H., & Sun, R. (2021). Working out the bipedal walking expenditure of energy based on foot morphology of different hominid genera: Implications for foot evolution. *Journal of Theoretical Biology, 519,* 110646. https://doi.org/10.1016/j.jtbi.2021.110646

Ichikawa, S., Kumai, T., Okunuki, T., Maemichi, T., Matsumoto, M., Yabiku, H., Liu, Z., Yamaguchi, R., Iwayama, A., Ayukawa, G., Akiyama, Y., Mitsui, H., & Niki, H. (2021). Comparison of foot posture and foot muscle morphology between lifesaver athletes and healthy adults. *Research in Sports Medicine*, 1–11. https://doi.org/10.1080/15438627.2021.2002330

James, C. S. (1939). Footprints and feet of natives of the Solomon Islands. *The Lancet*, *234*(6070), 1390–1394. https://doi.org/10.1016/s0140-6736(00)73938-9

Lieberman, D. E., Venkadesan, M., Werbel, W. A., Daoud, A. I., D'Andrea, S., Davis, I. S., Mang'Eni, R. O., & Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus Shod Runners. *Nature*, *463*(7280), 531–535. https://doi.org/10.1038/nature08723

Miller, E. E., Whitcome, K. K., Lieberman, D. E., Norton, H. L., & Dyer, R. E. (2014). The effect of minimal shoes on arch structure and intrinsic foot muscle strength. *Journal of Sport and Health Science*, *3*(2), 74–85. https://doi.org/10.1016/j.jshs.2014.03.011

Musiba, C. M., Tuttle, R. H., Hallgrímsson, B., & Webb, D. M. (1997). Swift and sure-footed on the savanna: A study of Hadzabe Gaits and feet in northern Tanzania. *American Journal of Human Biology*, *9*(3), 303–321. https://doi.org/10.1002/(sici)1520-6300(1997)9:3<303::aid-ajhb4>3.0.co;2-z

Rieck, T. (2020, March 23). *10,000 steps a day: Too low? too high?* Mayo Clinic. Retrieved April 28, 2023, from https://www.mayoclinic.org/healthy-lifestyle/fitness/in-depth/10000-steps/art-20317391#:~:text=The%20average%20American%20walks%203%2C000,a%20day%20every%20two%20weeks.

Sachithanandam, V., & Joseph, B. (1995). The influence of footwear on the prevalence of Flat Foot. A survey of 1846 skeletally mature persons. *The Journal of Bone and Joint Surgery. British Volume*, *77-B*(2), 254–257. https://doi.org/10.1302/0301-620x.77b2.7706341

Staff, F. E. (2021, March 16). *Flat feet*. familydoctor.org. Retrieved May 11, 2022, from https://familydoctor.org/condition/flat-feet/

Taddei, U. T., Matias, A. B., Ribeiro, F. I. A., Bus, S. A., & Sacco, I. C. N. (2020). Effects of a foot strengthening program on foot muscle morphology and running mechanics: A proof-of-concept, single-blind randomized controlled trial. *Physical Therapy in Sport*, *42*, 107–115. https://doi.org/10.1016/j.ptsp.2020.01.007

Wallace, I. J., Koch, E., Holowka, N. B., & Lieberman, D. E. (2018). Heel impact forces during barefoot versus minimally shod walking among tarahumara subsistence farmers and Urban Americans. *Royal Society Open Science*, *5*(3), 180044. https://doi.org/10.1098/rsos.180044

Wang, J., Tang, L., Tang, J., Chen, J., Gong, X., Qin, L., Huang, J., Deng, Y., Liu, X., Huang, W., Li, M., & Hu, N. (2022). The typically developing pediatric foot — the data of the 1744 children in China. *Foot and Ankle Surgery*, *28*(3), 347–353. https://doi.org/10.1016/j.fas.2021.04.005

Willems, C., Stassijns, G., Cornelis, W., & D'Août, K. (2017). Biomechanical implications of walking with Indigenous Footwear. *American Journal of Physical Anthropology*, *162*(4), 782–793. https://doi.org/10.1002/ajpa.23169

Zhao, X., Tsujimoto, T., Kim, B., Katayama, Y., & Tanaka, K. (2018). Increasing physical activity might be more effective to improve foot structure and function than weight reduction in obese adults. *The Journal of Foot and Ankle Surgery*, *57*(5), 876–879. https://doi.org/10.1053/j.jfas.2018.03.011

Acknowledgements.

We are especially thankful for the department of Anthropology at the University of New Mexico who provide essential help for recruiting participants. Thank you as well to Ian J. Wallace, Thomas S. Kraft and Nicholas B. Holowka for their help in analyzing data. Funding was provided by a UNM Maxine Graves Undergraduate Award to Chloé Lauer.

Appendix

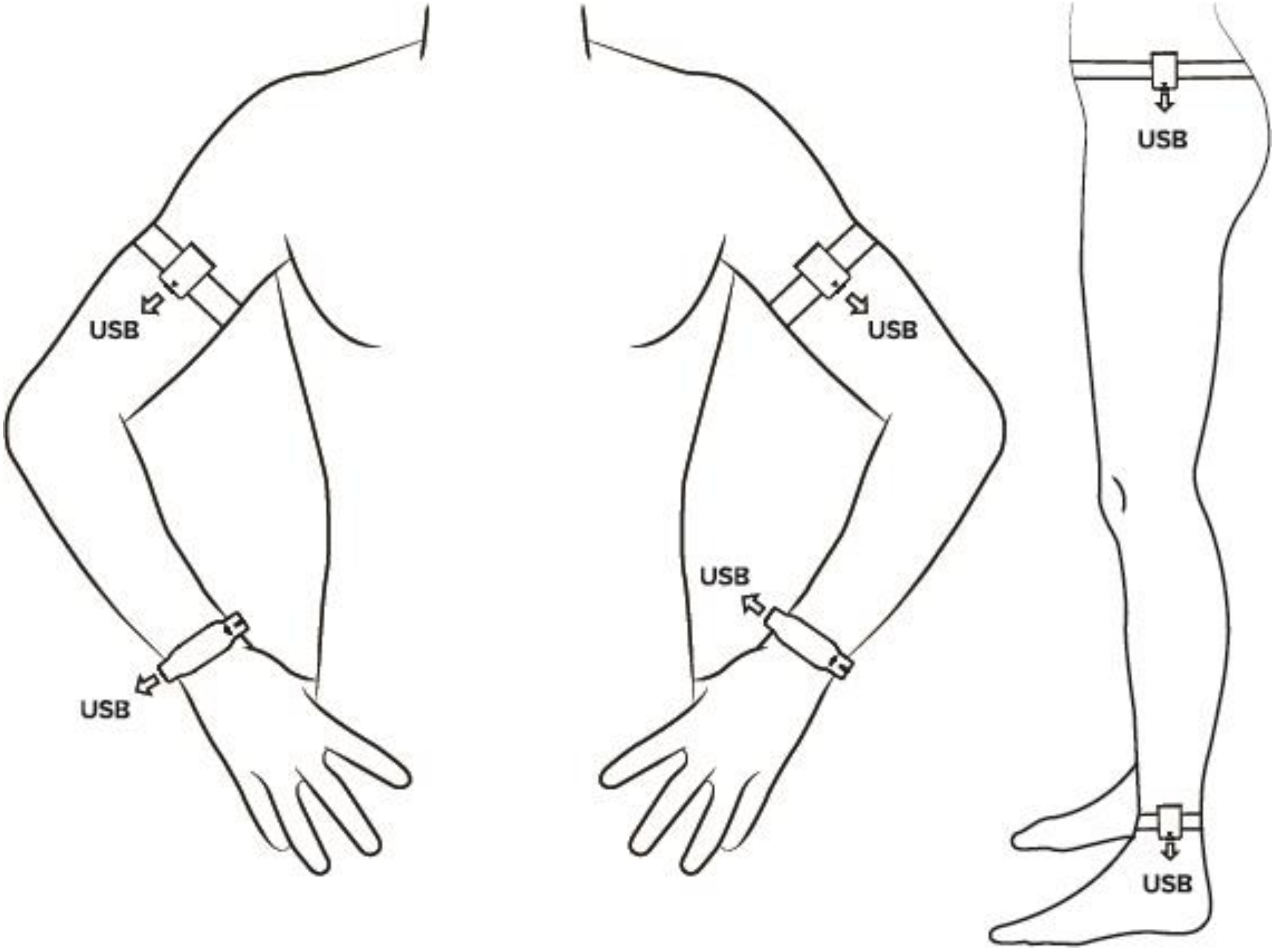

Figure 1. *Accelerometer mounting convention from the AX3 User Manuel.*

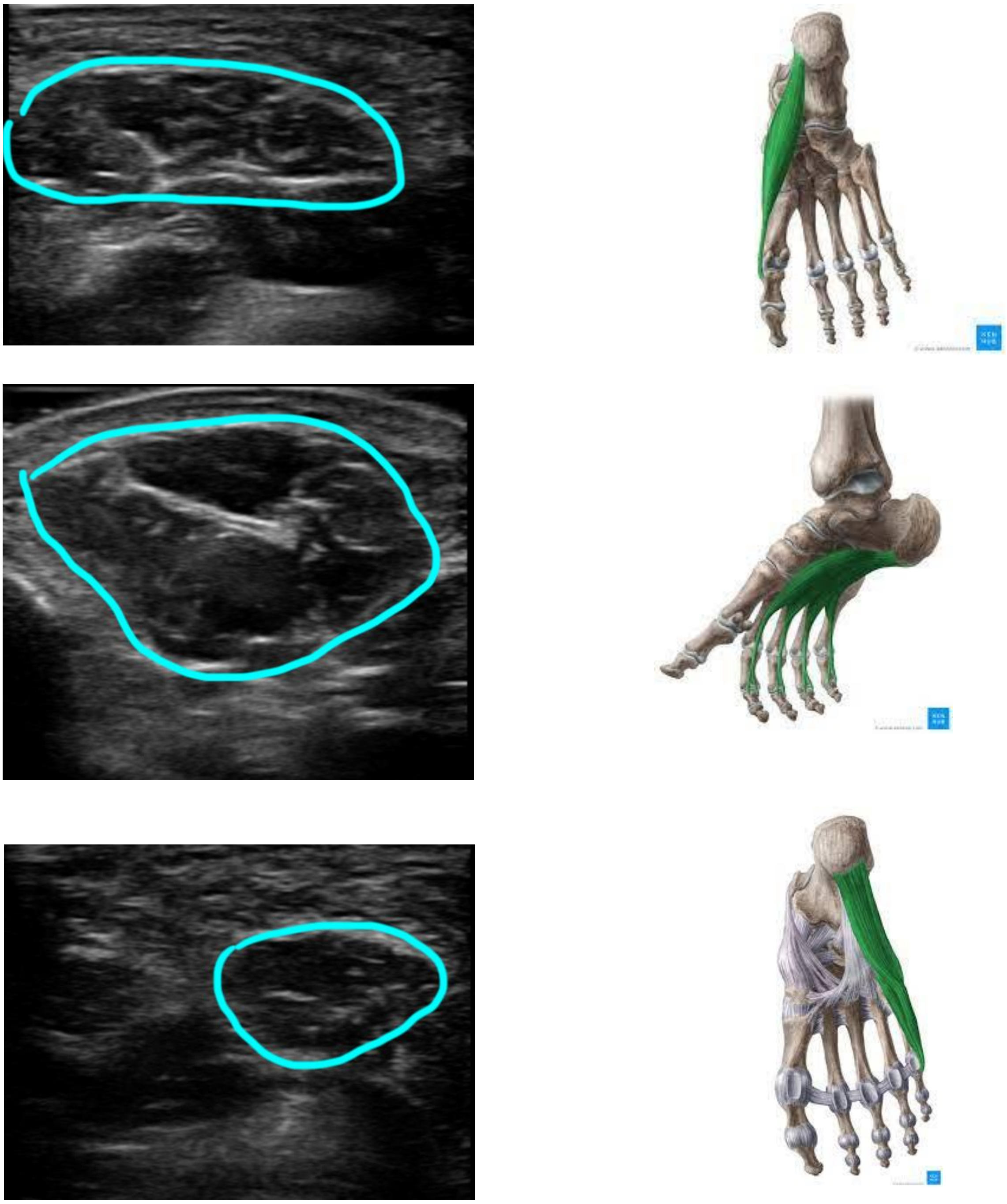

Figure 2. *Examples of cross-sectional areas of intrinsic foot muscles captured by ultrasound. From top to bottom: Abductor Hallucis, Flexor Digitorum Brevis, Abductor Digiti Minimi.*

Figure 3. *Recording of ground reaction forces. The participant walks at a self-selected speed on the force plate.*

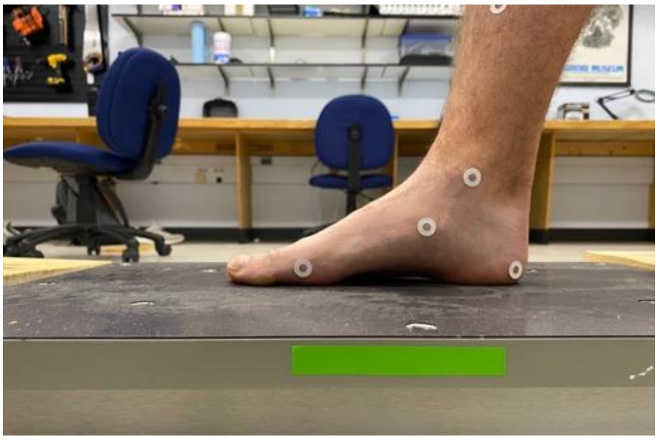

Figure 4. *Foot LA height was defined as the perpendicular distance between a marker on the navicular tuberosity and a line bisecting markers on the first metatarsal head and medial calcaneus.*

Figure 5. *Foot photo used to measure AHI. The participant is sitting on a chair (unloaded condition) and the arch is positioned between two wood plates.*

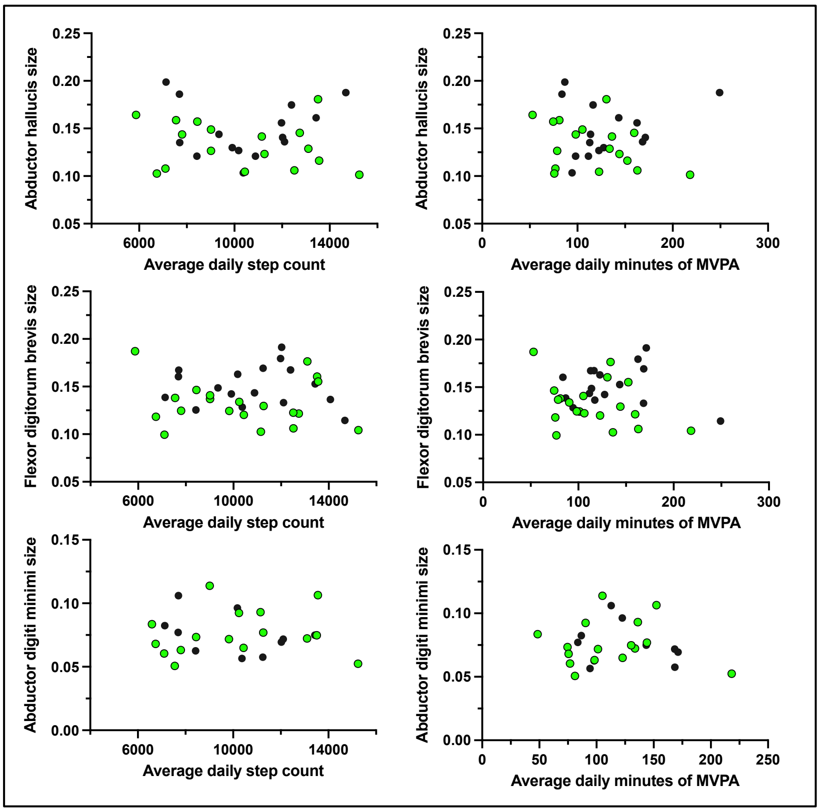

Figure 6. *Foot muscle cross-sectional areas vs. average daily step count (left) and moderate-to-vigorous physical activity time (right). Green dots are women.*

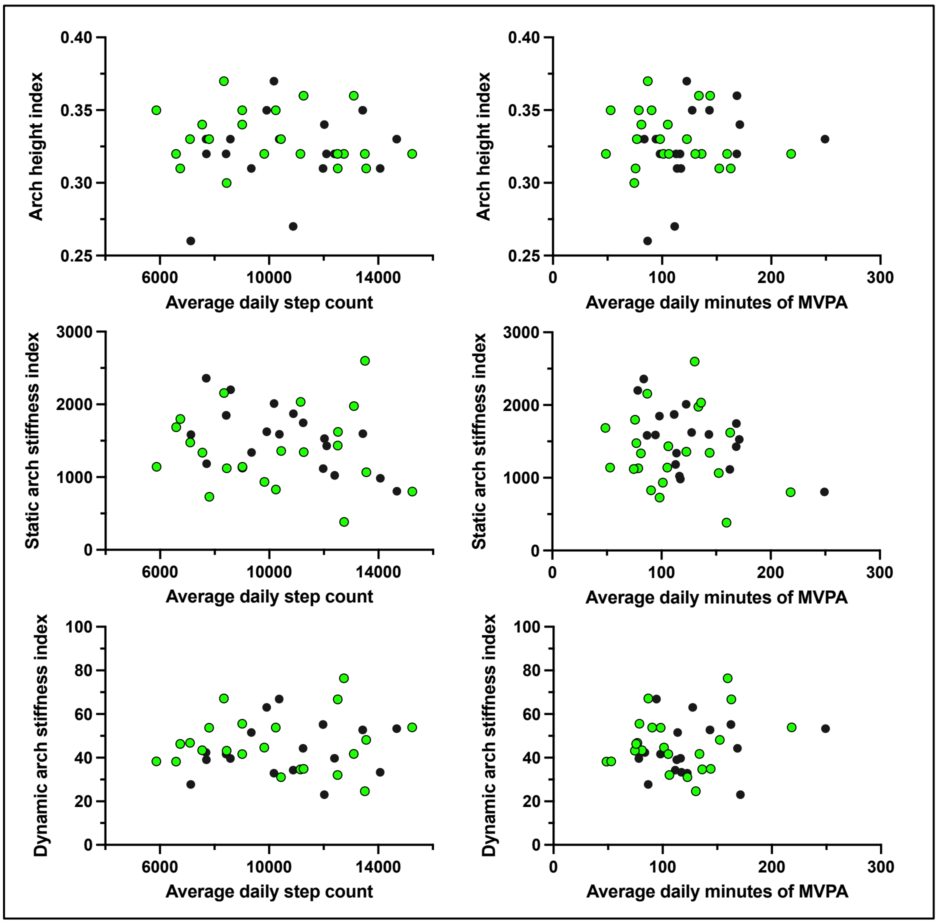

Figure 7. *Foot LA variables vs. average daily step count (left) and moderate-to- vigorous physical activity time (right). Green dots are women.*