American Journal of Biological Anthropology

WILEY

BRIEF COMMUNICATION OPEN ACCESS

Variation in the Angle of the First Pedal Ray Relative to the Midline of the Foot by Sex and Parity History

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Received: 3 September 2025 | **Revised:** 17 December 2025 | **Accepted:** 26 January 2026

Keywords: first metatarsal | pregnancy | sex differences | third metatarsal

ABSTRACT

Objective: Although pathological variations of the first pedal ray have been well-studied, non-pathologic variations, including those potentially linked to hormonal changes during pregnancy, have yet to be examined. Here we quantify the angle between the longitudinal axes of the first and third metatarsals and investigate variation in this angle between females and males and nulliparous and parous individuals.

Materials and Methods: Foot CT scans were accessed from Harborview Medical Center and the New Mexico Decedent Image Database. A 3D model was constructed in Avizo Lite 9.0.1 and landmarks were placed on the proximal and distal ends of the first and third metatarsal. The vectors between the landmark sets were used to represent the first and third metatarsal axes. The angle between the two axes was calculated in MATLAB. Wilcoxon Rank Sum tests were used to test for significant differences in this angle between (1) females and males, (2) nulliparous and parous females, and (3) nulliparous females and males.

Results: Females have a statistically larger angle compared to males (average 10.16° vs. 8.64°, $p = 0.03$). Parous females have a statistically larger angle than nulliparous females (average 10.44° vs. 8.74°, $p = 0.04$). Nulliparous females do not significantly differ from males ($p = 0.70$).

Discussion: We propose that the relatively larger angle in females is likely due to hormonal exposure, specifically relaxin, throughout pregnancy given that parous females have a relatively larger angle than both males and nulliparous females by 1.5°–1.7°, while nulliparous females share a similar average angle with males.

1 | Introduction

Modern humans are believed to have longitudinal arches, midtarsal joint mobility reduction, an adducted (i.e., aligned with the other metatarsals) and enlarged great toe, and 60°–90° of dorsiflexion of the metatarsophalangeal joints, all to accommodate bipedalism (e.g., Morton 1922, 1924a, 1924b; Hetherington et al. 1990). In hominins, bipedalism is thought to be predicated on this adducted first metatarsal (e.g., Morton 1924a; Elftman and Manter 1935; Lautzenheiser and Kramer 2013). An adducted orientation is believed to be critical in late stance, where the forefoot stabilizes and supports the weight of the body and the propulsive forces of bipedalism (Levine et al. 2014).

The first pedal ray, consisting of the first metatarsal and first cuneiform (Morgan et al. 2022), is critical in weight-bearing, as approximately 60% of propulsive and normal forces associated with body mass pass through the first ray from heel strike to toe off (Van Beek and Greisberg 2011). The great toe, or hallux, (which is distal to the first metatarsal) anchors the windlass mechanism by tightening the plantar fascia of the foot through dorsiflexion. This action stiffens the foot

Research Highlights

- Females have a statistically larger angle between the first ray and midline of the foot compared to males.
- Parous females have a statistically larger angle between the first ray and midline of the foot compared to nulliparous females.

when the heel is off the ground, allowing effective propulsion (Christensen and Jennings 2009). Together the first ray and hallux form the distal portion of the medial column of the foot and longitudinal arch. As such, any deviations from normal structure and function, such as first ray hypermobility, may play a role in foot pathologies (Morgan et al. 2022), potentially impairing human mobility, functional performance, and structural variation within the foot (Van Beek and Greisberg 2011; Morgan et al. 2022; Faltus et al. 2014).

The first pedal ray has positional variations that are often characterized as pathological states, such as hallux valgus, where the proximal phalanx deviates laterally and the first metatarsal head deviates medially (Kuhn and Alvi 2023). Hallux valgus is associated with first metatarsal abduction (Bu et al. 2023) and is more prevalent among females, with estimates ranging from two to 15 females affected for every male (Ray et al. 2019). This suggests that sex may influence the relationships among the bones of the first pedal ray and that female variability is higher than that of males. Other relationships among bones of the foot have not been shown to vary between males and females. For example, the angle between the long axes of the first and second metatarsal (also called the intermetatarsal angle) does not vary between males and females (e.g., Lautzenheiser and Kramer 2013). Frequently the potential for differences between males and females in first ray orientation is, however, not considered or, at least, not reported (e.g., Bu et al. 2023; Wu and Lam 2024; Çatal et al. 2025).

Pregnancy can have substantial implications for foot anatomy (Vico Pardo et al. 2018). One study suggests there is a 20% increase in weight associated with pregnancy (Vico Pardo et al. 2018), and the American College of Obstetricians and Gynecologists recommends females with a normal pre-pregnancy BMI to gain between 25 and 35 pounds (American College of Obstetricians & Gynecologists 2013). This increased body weight throughout pregnancy has been suggested to require longitudinal and transverse arch adaptations to absorb this increased weight (Vico Pardo et al. 2018). During pregnancy, there is also a 10-fold increase in the hormone relaxin, which is thought to be involved in relaxing the sacroiliac joint to accommodate for labor and delivery (Ponnapula and Boberg 2010). In addition to the pelvis, relaxin activates collagen degradation throughout the musculoskeletal system, where it increases length and laxity and decreases stiffness in soft tissues such as tendons, joints, ligaments, and cartilage (Dehghan et al. 2014; Owens et al. 2016; Wolf et al. 2014). Due to laxity of the foot ligaments, foot pronation increases from weeks 12 to 34 of gestation, along with an increase in the length of the foot and forefoot (Vico Pardo et al. 2018). These well-characterized changes to the foot that occur during pregnancy, combined with the high female variability in estimates of hallux valgus, suggest that parity history should be included when investigating sex differences in foot morphology.

This study aims to investigate variation in the angle between the long axes of the first and third metatarsals (which we call first pedal ray angle) between females and males and between nulliparous and parous individuals. For the purpose of this study, we use the term female to refer to individuals with a reproductive anatomy associated with bearing children and hence their bodies have, most likely, been subject to hormonal profiles associated with that anatomy (e.g., ovaries) and reproductive function (e.g., pregnancy), while recognizing that the term may have different meanings in the context of gender (O'Hanlan et al. 2018). We hypothesize that (1) a significant statistical effect of sex on the angle of the first pedal ray exists; (2) females from a sample with unknown parity history will have a significantly larger first pedal ray angle compared to males; and (3) that when parity history is known, parous females will have a significantly larger angle than nulliparous females.

2 | Materials and Methods

To investigate variation in first pedal ray angle between females and males, we utilized CT scans from a total of 57 individuals. We accessed previously collected, de-identified simulated weight-bearing computed tomography (CT) scans from the Harborview Medical Center (Seattle, WA) database ($n = 35$) (approved by the University of Washington Institutional Review Board) and non-weight-bearing CT scans from the New Mexico Decedent Image Database (NMDID) ($n = 22$) (Edgar et al. 2020). The sample consists of 26 biological females and 31 biological males between the ages of 18 and 70 (Table 1). No information on parity history was available for these individuals. Only individuals that did not have a visible pathology (e.g., arthrosis) in the foot of interest were included in the study.

TABLE 1 | Sample age class information.

Age range	Males	Females (no parity information)	Parous females	Nulliparous females
18–30	15	7	10	15
31–40	4	6	9	11
41–50	5	7	11	6
51–60	5	1	7	5
60–70	2	5	—	—

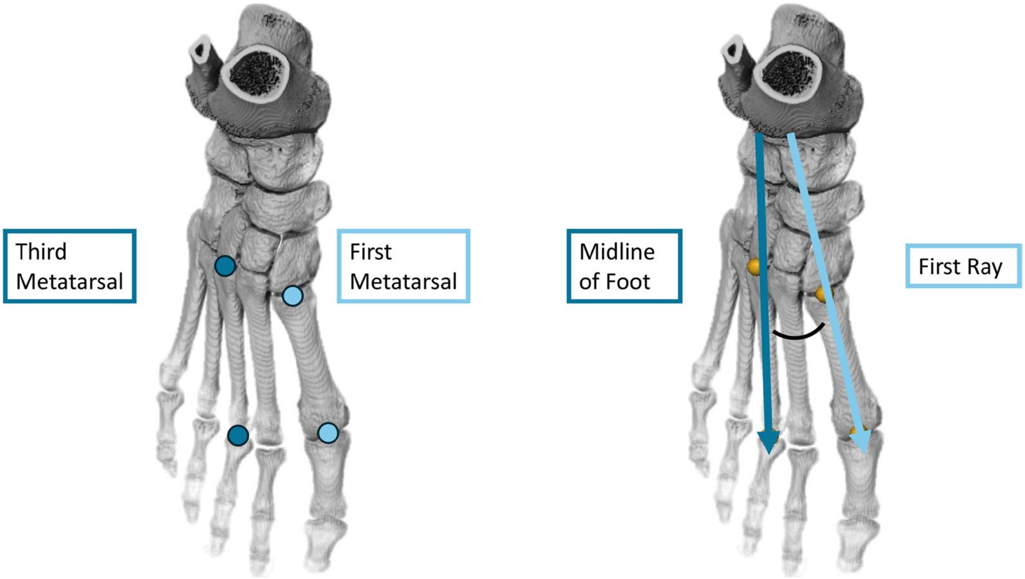

FIGURE 1 | CT scan of the right foot. On the left, the dark blue landmarks demarcate the borders of the third metatarsal, and light blue landmarks demarcate the borders of the first metatarsal. On the right, the dark blue and light blue vectors indicate the longitudinal axes of the third and the first metatarsals, respectively. These two vectors create the first pedal ray angle.

To investigate if parity history impacts this angle, we accessed an additional 74 CT scans of females ages 18–70 from the NMDID (Edgar et al. 2020) (Table 1). This sample consists of 37 females with one or more pregnancies, or parous individuals, and 37 females with no parity history, or nulliparous individuals. Information about parity history was reported by the next of kin (Edgar et al. 2020). Individuals excluded from this study include those who were outside of the 18–70 age range, had a visible pathological deformity of the lower extremity, and/or did not have parity information recorded.

Landmarks were placed on the proximal and distal most ends of the first metatarsal and third metatarsal in Avizo Lite 9.0.1 (Figure 1; FEI Visualization Sciences Group 2015). The vectors between these landmarks represented the long axis of the first and third metatarsals. We used custom scripts in MATLAB R2022b (Mathworks Inc., Natick, MA) to calculate the angle between the two axes. To test for repeatability, 10 subjects were randomly selected, the landmarks were recollected, and angles remeasured an additional two times. There were no significant differences ($p = 0.55$) in the angles among the three trials (i.e., the original data and two additional trials) based on a Kruskal–Wallis test.

We used MATLAB R2022b to calculate angle summary statistics, including mean, maximum, minimum, and standard deviation. Wilcoxon Rank Sum tests were used to test for differences in the first pedal ray angle between (1) females and males, (2) nulliparous and parous females, and (3) nulliparous females and males. As this study included data from both weight-bearing and non-weight-bearing CTs, we additionally used Wilcoxon Rank Sum tests to investigate differences in the two scan modalities for the female–male comparison sample. We also tested for significant relationships between first pedal ray angle and cadaver mass, cadaver height, and age in the parous versus nulliparous sample and age in the female versus male sample (height and body mass information were not available for the Harborview sample) using Spearman's rank correlations. Non-parametric statistics were run for all analyses due to the relatively small sample sizes of each group.

TABLE 2 | Females versus males angle summary (°).

	All angles	Females	Males
Mean	9.31	10.16	8.64
Max	14.39	13.88	14.39
Min	4.37	5.83	4.37
StD	2.61	2.64	2.43

3 | Results

3.1 | Females Versus Males

No significant difference was found in the first pedal ray angle between the weight-bearing and non-weight-bearing CT scans ($p = 0.49$). The first pedal ray angle ranges from 4.37° to 14.39° in the sample including females with unknown parity history and males (i.e., the combined sample from Harborview Medical Center and New Mexico Image Decedent Database), with an average of 9.31° (Table 2). Females have a significantly larger angle (average of 10.16°) compared to males (average of 8.64°) ($p = 0.03$; Table 2; Figure 2). There was no significant relationship between age and first pedal ray angle ($r = 0.07$, $p = 0.61$).

3.2 | Nulliparous Versus Parous

Parous females have a significantly larger angle ($p = 0.04$) on average than nulliparous females (Table 3; Figure 3). The average angle of nulliparous females is 8.74°, ranging from 2.27° to

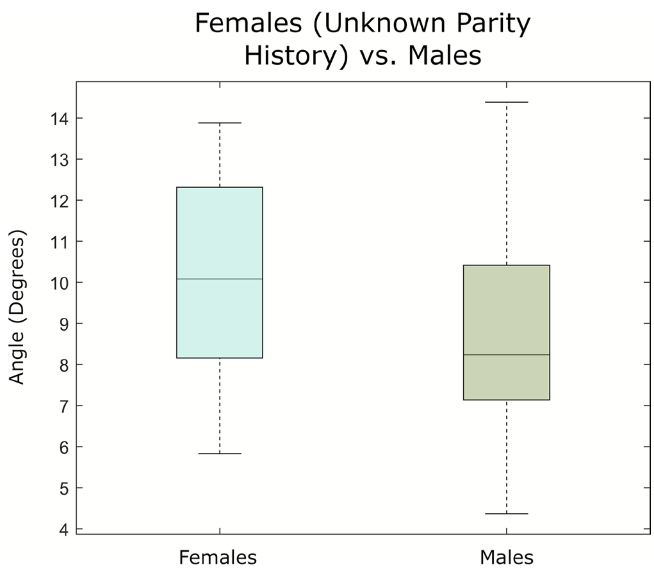

FIGURE 2 | Boxplot of variation in the first pedal ray angle between females and males.

TABLE 3 | Nulliparous versus parous females angle summary (°).

	Nulliparous	Parous
Mean	8.74	10.44
Max	14.17	16.82
Min	2.27	3.66
StD	3.15	3.28

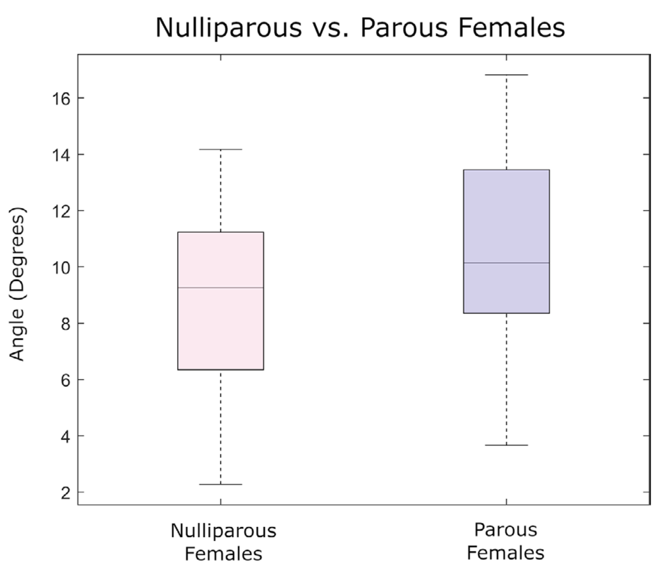

FIGURE 3 | Boxplot of variation in the first pedal ray angle between nulliparous and parous females.

14.17°. The average angle of the parous females in this sample is 10.44°, ranging from 3.28° to 16.82°. There were no significant relationships between first pedal ray angle and age ($r=0.04$, $p=0.72$), cadaver mass ($r=0.05$, $p=0.67$), or cadaver height ($r=-0.04$, $p=0.76$).

3.3 | Nulliparous Females Versus Males

There are no significant differences between nulliparous females and males ($p=0.70$).

4 | Discussion

The results of this study suggest that non-pathologic variation exists in the angle between the long axes of the first and third metatarsals. More specifically, we find that females have a significantly larger angle than males, consistent with our prediction. Although other foot angular relationships have not demonstrated significant differences between males and females (e.g., Lautzenheiser and Kramer 2013), our finding is consistent with previous studies demonstrating sex differences in other aspects of foot morphology. For example, in a study of 160 males and females of modern European-American descent, researchers could determine biological sex through the height of the talus and the length of the third cuneiform with 93.6% accuracy (Harris and Case 2012). Multiple studies have additionally found that males tend to have longer and wider feet than females (Luo et al. 2009; Inayah 2025).

It is possible that some of the changes seen in this study could be the result of differing footwear preferences between females and males. Previous research has found that 59% of females wear high heels from one to eight hours a day (Zeng et al. 2023). The use of high heels with their restrictive toe box can lead to claw toes, hallux valgus, and calluses, and destabilize gait through shorter steps and stride length (Lorkowski and Pokorski 2023). This would also be consistent with previous studies that suggested there may be differences in bony foot morphology related to the footwear (Trinkaus 2005; Zipfel and Berger 2007; Sorrentino et al. 2020; Albee 2022; Harper 2023).

The sex differences demonstrated here are potentially biomechanically and functionally important because any anatomical variation within the foot can have an impact on foot mobility and overall stability. Anatomically, the first and third metatarsals are attachment sites for muscles important in gait and stability, such as the transverse adductor hallucis muscle (Arakawa et al. 2003). The adductor hallucis attaches to the proximal phalanx of the great toe to adduct and flex the great toe at the metatarsophalangeal joint (Owens and Thordarson 2001) and stabilizes the transverse arch of the foot and metatarsal heads during push off (Dygut and Piwowar 2022). Given the documented sex-based differences in gait—for example, females have a higher cadence and spend more time in stance and the first double support phases compared to males, and males have an increased stride length and swing phase with an overall longer duration of the gait cycle (Suner-Keklik et al. 2023)—future research should include first pedal ray angle and other morphological variation of the foot as variables in gait analyses.

To understand the mechanism driving variation in first pedal ray angle in females compared to males further, we additionally compared first pedal ray angle in nulliparous and parous females. The impact of pregnancy on the lower extremity musculoskeletal system has been documented in the past (Segal et al. 2013; Ponnapula and Boberg 2010; Block et al. 1985). Throughout pregnancy, the foot gets larger, wider, and increases in volume and exhibits increased pronation (Segal et al. 2013). The talus drops 1 cm corresponding to a drop in arch height, due to laxity of the spring ligament and attenuated tibialis posterior tendon (Ponnapula and Boberg 2010), with an increased range of motion seen in the subtalar and first metatarsophalangeal joint (Block et al. 1985). This loss of arch height appears to be a permanent change (Segal et al. 2013). In a case–control study of postpartum and nulliparous females, postpartum individuals had a significantly higher prevalence of foot pain compared to their control counterparts (Vullo et al. 1996). A separate study found that more than 50% of 100 postpartum individuals reported foot, ankle, and leg swelling, an unsteady gait, and increased foot width during their pregnancy (Ponnapula and Boberg 2010). In our study, we discovered a significant positive difference in the angle between the first and third metatarsals in parous compared to nulliparous individuals. The presence of a significant difference in first pedal ray angle suggests that pregnancy affects aspects of foot morphology outside of the arch. More work needs to be done to investigate what other differences in foot anatomy are associated with pregnancy.

The mechanism of the differences demonstrated here likely lies in the connective tissue, such as cartilage, bone, blood, adipose, tendons, and ligaments (Kamrani et al. 2023), and its structural response to hormones like estradiol and relaxin. These hormones decrease the collagen content of connective tissue, especially at times of high estrogen and relaxin concentration, such as the ovulatory phase or mid cycle (Silke 2011) and throughout pregnancy (Segal et al. 2013). Collagen maintains strength and stiffness, and a decrease in collagen can cause laxity in the various connective tissues throughout the body, including the foot (Dehghan et al. 2014). Additionally, increased repetitive loading, such as through exercise, causes microdamage, which can reduce the integrity of the tissue and increase laxity, particularly in areas that experience high forces (Silke 2011). The first ray is an area that already experiences high forces (Van Beek and Greisberg 2011) that likely increase during pregnancy with higher abdominal mass. Additionally, with increased pronation, the medial foot experiences increased time under pressure, particularly the hallux (Dodelin et al. 2020). Thus, this larger angle in parous females is likely due to the increased estradiol and relaxin females are exposed to throughout their pregnancy. Differences in first pedal ray angle, therefore, may be due more to pregnancy than to biological sex. This is supported by the lack of significant difference between males and nulliparous females. Future work should document changes in foot morphology throughout pregnancy.

While this research is informative with regard to variation in foot morphology and its relationship to sex and parity, it is not without limitations. The first limitation involves the use of non-weight-bearing and weight-bearing CT scans. Although there was no significant difference found in first pedal ray angle between the two CT scanning modalities, there may still be an unaccounted-for, unmeasured effect. An additional limitation is the relatively small sample sizes for comparing parity history due to our exclusion criteria and low reporting of parity history within the NMDID. Despite this, however, we were still able to detect a significant difference among the groups, suggesting that the sample size had appropriate statistical power. Finally, obesity, or a body mass index (BMI) of greater than or equal to 30, has been correlated with changes in foot morphology such as acquired pes planus, or flat feet, as well as rearfoot valgus and forefoot varus (Hande et al. 2025; Richie Jr 2007). Although we did not find a significant relationship between cadaver mass and first pedal ray angle, body mass information was unavailable for many of the subjects in the study. Future work should investigate the relationship between body mass and variation in foot morphology, particularly in reference to parity history.

5 | Conclusion

As with many aspects of the human body, non-pathologic variation of the first pedal ray angle exists, with a larger angle in females than males on average. This angular difference is associated with parity, as nulliparous individuals do not significantly differ from males. Since the first pedal ray plays an essential role in weight-bearing throughout the gait cycle (Van Beek and Greisberg 2011), future research should focus on the clinical implications, if any, of different pedal ray angles. Mobility, stability, gait, and injury risk may differ in the general and postpartum populations, and other potential areas of foot morphology may be influenced by pregnancy. Additionally, since hormones affect ligaments and hence joint stability and motion throughout the body, parity history should be a standard variable collected in musculoskeletal or biomechanical projects.

Author Contributions

Paige S. Whitman: investigation, writing – original draft, visualization, writing – review and editing, formal analysis, conceptualization. **Addie E. C. Lomax:** writing – review and editing, formal analysis, investigation. **Patricia Ann Kramer:** investigation, writing – review and editing. **Christine M. Harper:** conceptualization, methodology, software, formal analysis, supervision, writing – review and editing, resources, investigation.

Acknowledgments

The authors would like to thank the patients, deceased individuals, and their next of kin whose data was included in this study. The authors would additionally like to thank Steven G. Lautzenheiser for assistance with initial data access and helpful conversations. P.A.K. thanks S.K. Benirschke, MD, Jerome Debs Endowment Chair in Orthopedic Traumatology at UW, for the ongoing support of this research and for our many conversations about form and function.

Ethics Statement

The secondary use of data collected at Harborview Medical Center was approved by the University of Washington's Institutional Review Board. All data for deceased individuals was accessed as de-identified data after receiving permission from the New Mexico Decedent Image Database.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions, including respect for the deceased and their family and data use agreements with both Harborview Medical Center and New Mexico Decedent Image Database.

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