

The Effect of Added Weight on Foot Anthropometry in Pregnant Women and Nulligravida Women

Kathryn D Harrison

West Virginia University

Krystal Thomas

West Virginia University

Corrie Mancinelli

West Virginia University

Petronela Meszaros

West Virginia University

Jean L McCrory (✉ jlmccrory@hsc.wvu.edu)

West Virginia University <https://orcid.org/0000-0003-2779-8262>

Research article

Keywords: pregnancy, foot, alignment, anthropometry, medial longitudinal arch, arch height

Posted Date: August 12th, 2019

DOI: <https://doi.org/10.21203/rs.2.12627/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Abstract

Background Foot anthropometry is altered by pregnancy. It is unknown if these changes are due to increased bodyweight and/or hormonal concentrations. The purpose of our study was to examine the effect of added weight on foot anthropometry in pregnancy. Methods Fifteen primigravid women and 13 nulliparous controls participated. Controls were matched to pregnant women based on self-reported pre-pregnancy weight. After informed consent, data were collected on pregnant participants in each trimester and post-partum. Foot length, width, arch index, arch height index, arch rigidity index, and arch drop were assessed. Subsequently, pregnant participants in their first two trimesters donned a weighted pack such that total weight difference from pre-pregnancy weight was 124N. Foot measurements were repeated. Third trimester participants were only measured without a pack as they were at full-pregnancy weight. In post-partum, bodyweight plus pack-weight equaled third trimester weight. For control participants, bodyweight plus pack-weight equaled third trimester weight of the pregnant participant to whom they were matched. A MANOVA was performed with the independent variables of trimester, weight condition, and leg. Tukey post-hoc analyses were performed when appropriate ($\alpha=0.05$). Results Arch drop increased by 18% ($p=0.007$) and arch rigidity index decreased by 1% ($p=0.001$) while weighted across both pregnant and control groups. Increase in foot length and width and decrease in arch height index with added weight was only greater in pregnant participants compared to the control participants ($p<0.05$). Conclusions Adding weight produced changes in arch drop and arch rigidity index. Weight plus pregnancy was related to further alterations in anthropometry. Increased pregnancy hormone concentrations likely affect foot anthropometry in primigravid women.

Background

A number of physiological and anthropometric changes occur during pregnancy and persist post-partum. Pregnant women experience substantial weight gain (1). Due to the increasing abdominal volume associated with the growing fetus, an anterior shift in the center of mass (2), increasing spinal lordosis (3), increasing thoracic extension (4), and decreased strength of the abdominal musculature (5) are noted during pregnancy. An increased serum concentration of relaxin increases the laxity of the sacro-pelvic ligaments to broaden the pelvic inlet to allow for childbirth (6). The effects of relaxin are also seen in peripheral joints, as increased joint laxity in the hand, foot, and knee are noted during pregnancy (7, 8).

Anthropometric alterations specific to the foot have been widely reported. Anecdotally, women have described increased shoe size following pregnancy (9–11). Objective studies have reported increased foot length, width, and volume (7, 12). Nyska et al. (1) noted a greater area of the foot in contact with the ground during pregnancy, while others have indicated a decreased arch height (13, 14).

However, these alterations are also seen in obese individuals. Increased body weight and/or situational load bearing, such as wearing a rucksack, are related to increased plantar contact area, increased foot length and width, and decreased arch height (15–18). It is not known if the changes seen during pregnancy are due to the increased ligamentous laxity related to serum relaxin or to the increased body weight associated with pregnancy. Once stretched beyond the elastic region, ligaments do not return to their original length (19). Thus, these changes to foot anthropometry are likely to persist post-partum (14). The altered foot shape may be related to impaired foot function (14) and increased reports of foot pain in post-partum women (20). If this

pain does not resolve, this could become a significant life-long concern. A better understanding of changes in foot structure during pregnancy, and their relationship to pain, may allow for improved methods of prevention and treatment.

We have previously reported the changes in foot anthropometry over the course of a first pregnancy (21). Specifically, we examined foot length and width, arch index, arch height index, arch drop, and arch rigidity index (21). Foot length increased significantly such that by the third trimester, the feet of pregnant participants were 3% longer than controls, and this increased length persisted post-partum (Cohen's D = 0.63 with a medium effect size) (21). Arch index also tended to be greater in the third trimester, indicating a lower arch (Cohen's D = 0.40 with a small effect size), although this was not noted post-partum (21). Thus, this transient change may be due to added weight, increased laxity secondary to pregnancy hormones, or edema of the feet, all of which occur during pregnancy.

The purpose of this study was to examine the effect of added weight on foot anthropometry in primigravida women and nulligravida controls. We hypothesized that added weight, regardless of pregnancy status, will result in increased foot length, width, arch index, and arch drop and decreased arch height index and arch rigidity index. Furthermore, we hypothesized that these changes will be greater in the primigravida women, particularly in the third trimester, due to the combined effects of added weight and the pregnancy-related hormones.

Materials And Methods

Participants

For this preliminary study, detection of only very large effect size was sought. To detect a very large effect size when $\alpha = 0.05$ and $\beta = 0.80$, a sample size of 11 per group was required. The investigators expected a dropout rate of 25% amongst pregnant women. Thus, fifteen primigravid women and thirteen nulliparous controls participated in this study. Each control participant was matched to a pregnant participant based on her self-reported pre-pregnancy body weight.

Participant demographics are shown in Table 1. Control participants were significantly younger than the pregnant participants ($p < 0.001$). Mass was significantly different between groups ($p = 0.003$), as pregnant participants were significantly heavier than the control participants in their second and third trimesters, but not in their first trimester or post-partum.

Table 1: Subject demographics (mean \pm standard deviation)

Participants were recruited through advertisements placed around the university community and obstetrics healthcare facilities. Pregnant women were also recruited from the clinical obstetrics practice of one of our co-authors (PM). Participants were screened over the telephone to determine if they met the enrollment criteria for the study. Inclusion criteria included being between 18 and 45 years old, in a first pregnancy (pregnant group only), or never-pregnant (control group only). Each control participant must have also matched the self-reported pre-pregnancy weight ($\pm 15\text{N}$) of a pregnant participant. Exclusion criteria included a history of severe lower limb injury (grade 3 sprain or higher, fracture, or surgery). Additionally, potential participants were

excluded if they had lost more than 15% of body weight, or if they were considered by their obstetrician to have a complicated pregnancy (pregnant group only).

Experimental procedures

Data collection took place either at the obstetrics clinic or in our laboratory, based upon the participant's preference. At her initial visit, the experimental procedures were explained to each participant. Following this, written informed consent to participate was obtained from each subject in accordance with the Declaration of Helsinki. The study was approved by the university Institutional Review Board (Protocol # H-23586). Pregnant participants were asked to make a total of four visits: once during the last month of each trimester, and once one to three months post-partum. Control participants made one study visit.

Each participant was asked to remove all footwear and socks. Current body weight was measured with a standard bathroom scale (Model 2020W, Taylor Precision Products, Oak Brook, IL). Anthropometric measurements were taken bilaterally on each participant, with the first leg measured randomly selected at each visit. All of the measurements were taken by the same investigator (KDH). With the participant in her natural bipedal stance, the length of each foot was assessed with a standard anthropometer (Model 01291, Lafayette Instrument Company, Lafayette, IN). Foot length was defined as the distance from the most anterior tip of the toes to the most posterior part of the heel. Foot width was then assessed as the mediolateral distance between the most medial and most lateral aspects of each foot.

Arch index, an indirect indicator of arch height, was measured using an inked footprint according to the methods of Cavanagh and Rodgers (22). Specifically, each participant was asked to stand on the bathroom scale. She was instructed to place one foot on an inkpad (Aetrex Harris mat, Teaneck, NJ) located 15 cm medial to the scale. The inkpad is designed so that the participant's foot did not contact the ink; rather, the ink was located on the underside of a rubber bladder that contacts the paper when weight was placed on it. The participant was instructed to slowly transfer her weight to the inkpad until the scale read half of her weight. Following this, she lifted her foot from the inkpad and the inked footprint was removed from the mat. A line was drawn on the footprint from the most posterior aspect of the heel to the tip of the second toe. The distance from the anterior forefoot (not including the toes), to the posterior heel was measured along this line. The distance was divided into thirds and corresponding marks were made along the line on the footprint such that the foot was divided into the forefoot, midfoot, and rearfoot. The area of the midfoot and the area of the total foot were measured using Image J software (NIH, Bethesda, MD). Arch index is calculated as the area of the midfoot divided by the total area of the foot (22). Thus, a larger number represents a lower arch. Arch index measures have intra-rater reliability of 0.92323).

The Arch Height Index Measurement System (AHIMS, JAKTOOL Engineered System, Cranbury, NJ), was used to assess arch height index, arch drop, and arch rigidity index according to the methods of Pohl and Farr (24). These measures have an intra-rater reliability between 0.87–0.92 (24, 25). The first measurements were taken with the participant seated. The ankle position was standardized such that the line between the first metatarsal head and the lateral malleolus formed a 120° angle with the line from the lateral malleolus to the fibular head, as assessed with a goniometer. Using the AHIMS elevated on two wooden blocks to leave the

medial longitudinal arch unsupported, three measurements were obtained on each foot: total foot length (foot length including the toes), truncated foot length (distance from the posterior heel to first metatarsal head), and dorsal height (height to the dorsum at one half of total foot length). The calipers in the AHIMS were then loosened to allow for the participant to stand such that half of her body weight was on the bathroom scale and half was on the wooden blocks. The same three measurements were then obtained in the standing position. Seated arch height index was calculated as seated dorsal height ÷ seated truncated foot length. Standing arch height index was calculated as standing dorsal height ÷ standing truncated foot length. A larger value indicates a higher medial longitudinal arch (24). Arch drop was calculated as seated dorsal height – standing dorsal height. Arch rigidity index was calculated as standing arch height index ÷ seated arch height index (24). An arch rigidity index of 1 indicates a perfectly rigid arch and lower numbers indicate a more flexible arch.

To assess the effect of added weight on these measurements of foot anthropometry, a weighted backpack (Jansport, Appleton, WI) worn on the participant's anterior trunk was used. Pregnant participants in their first two trimesters wore the pack such that total weight difference from their pre-pregnancy weight was 124N, which was based on the average weight gain of pregnant participants in a previous study (26). All standing measurements were repeated while the participants wore this pack. Third trimester participants did not wear a pack as they were at full-pregnancy weight. For post-partum participants, their body weight plus the weight of the pack equaled their third trimester weight. For control participants, their body weight plus the weight of the pack equaled the third trimester weight of the pregnant subject to whom they were matched. Thus, control participants had one visit and performed two conditions (normal weight and added weight); pregnant participants had four visits. They performed two conditions in visit 1 during their first trimester (current weight and added weight), two conditions in visit 2 during their second trimester (current weight and added weight), one condition in visit 3 during their third trimester (current weight), and two conditions in visit 4 during postpartum (current weight and added weight).

Statistical Analysis

All statistical analyses were performed in SPSS software (version 21, Armonk, NY). participant demographics (i.e. age, height, mass at each trimester, weeks pregnant) were compared between groups and trimesters using an ANOVA ($\alpha = 0.05$). The same data values were entered into the statistical spreadsheet for the "natural" and "weighted" conditions for the participants in their third trimester because at this point, their natural condition was considered their maximal weight. A repeated measures ANOVA was performed on each dependent variable, with the independent variables of trimester (control, first, second, third, and post-partum), weight condition (natural or weighted), and leg (L or R) in each analysis. The dependent variables analyzed were foot length, foot width, arch index, standing arch height index, arch drop, and arch rigidity index. Main effects and interactions were assessed in the statistical model. However, the results of the main effect of trimester were presented in a previous manuscript (21), so this manuscript focuses primarily on the effects of added weight, as well as the weight x trimester interaction. Tukey post-hoc analyses were performed if appropriate ($\alpha = 0.05$).

Results

Main effect of Added Weight

Arch drop and arch rigidity index were both significantly altered by adding weight to the participants. Arch drop increased by 18% ($p = 0.007$) and arch rigidity index decreased by 1% ($p = 0.001$) in the weighted condition across both the pregnant and control groups. Data are provided in Table 2. No other variables were significantly different between the natural and weighted conditions.

Main effect of Leg

Leg tested (left or right) was included in our statistical model because the legs were not independent observations. Also, we wanted to ascertain if the effect of added weight was the same bilaterally. No differences were noted between legs on any variables except standing AHI ($p = 0.04$). The right standing AHI (0.319 ± 0.025) was lower than the left standing AHI (0.326 ± 0.026), indicating a slightly lower arch on the right leg in all participants. No interactions involving leg were significant (trimester x leg or weighted condition x leg). Thus, pregnant women did not demonstrate a greater asymmetry of standing AHI between the left and right legs than did the controls.

Interaction between Added Weight and Trimester

The condition (natural, weighted) x trimester interaction was significant in several variables (Table 2). Increase in foot length with added weight was greater in pregnant participants vs controls, with the effect of the added weight increasing throughout pregnancy ($p = 0.005$), although the values were not statistically different between the trimesters/post-partum in the pregnant participants.

Table 2: Foot anthropometric variables in natural and weighted conditions (mean \pm standard deviation).

Similarly, the condition x trimester interaction was significant in the foot width measure ($p = 0.05$) as the foot width was greater in the weighted condition in the latter trimesters such that in the weighted condition, the foot width of the pregnant women in the second and third trimesters and post-partum was significantly greater than control group. Foot width in the third trimester and post-partum was significantly greater than during the first trimester, and it was greater post-partum than it was in the third trimester. Arch index also saw a condition x trimester interaction ($p = 0.037$), such that when the participant was weighted, arch index was greater in the second and third trimesters and postpartum than in the controls.

Finally, a significant condition x trimester interaction was noted in the standing arch height index variable ($p = 0.007$). In the weighted condition, controls displayed a larger arch height index value than in the first and second trimesters and postpartum; pregnant participants in the weighted condition in their second and third trimesters and post-partum displayed a greater arch height index value than when they were in their first trimester, and their weighted arch height index values in their third trimester were less than in the second trimester. There were no significant interaction effects for arch drop or arch rigidity index.

Discussion

The purpose of this study was to examine the effect of added weight on foot anthropometry in pregnant women and non-pregnant controls. Results for the main effect of "trimester" have been published in (21). The current research paper is focused on the effect of added weight on foot anthropometry as well as the interaction between added weight and trimester. We hypothesized that added weight will result in increased foot length, width, arch index, and arch drop and decreased arch height index and arch rigidity index. We also hypothesized that these changes will be greater in the pregnant women, particularly in the third trimester, due to the combined effects of added weight and the pregnancy-related hormones.

Our results partially support these hypotheses. Simply adding weight to the participants via a weighted pack produced significant changes in arch drop and arch rigidity index. All participants displayed a greater arch drop while weighted, and a corresponding lower arch rigidity, indicating a more flexible arch, compared to when they were in the "natural" condition. Because these alterations were seen not only in the pregnant participants, but equally in the control participants who did not have the circulating pregnancy hormones such as relaxin, this indicates that marked weight gain alone will alter medial longitudinal arch anthropometry. Hills et al. reported increased contact of the midfoot with the ground in obese individuals (16).

Furthermore, added weight plus pregnancy, as in the condition x trimester interaction, was related to additional alterations to foot anthropometry. This suggests that other pregnancy-associated factors in addition to weight, such as increased hormone concentrations (e.g. relaxin), may play a role in foot anthropometry changes in pregnancy. Foot length and width were significantly greater as pregnancy progressed (21), but this difference was exacerbated in the weighted condition in the current analysis.

Arch index was greater in the second and third trimesters and post-partum in the weighted condition compared to controls, indicating more contact area of the midfoot with the ground. Previously, we reported that arch index was only greater in the third trimester when compared to controls when examining the effects of trimester alone (21), and this effect was not seen post-partum; thus, the current study signifies that adding weight during pregnancy, when relaxin concentration is high, results in a greater arch index and a presumably lower medial longitudinal arch, than just pregnancy alone. While lower leg edema may affect the arch index measure during pregnancy, a greater arch index was also noted post-partum when swelling would not be a concern (27). The lower arch index is not due to a greater bodyweight after the pregnancy because by the time the participants were tested post-partum, their weight had returned to its pre-pregnancy value. Our data support the conclusion that the medial longitudinal arch is more lax following pregnancy, and the carrying of an additional weight may result in more arch deformity than prior to the pregnancy. As it would be expected that a post-partum women carry a child in her arms for the next few years, this increased laxity of her medial longitudinal arch may be a source of foot dysfunction or pain.

Arch height index is another measure that corresponds to the height of the medial longitudinal arch. A smaller height to the dorsum and/or a longer foot would result in a smaller arch height index, indicating a lower arch. In our previous study, we reported that no alterations were noted due to the main effects of trimester alone (21), despite the fact that foot length was increased during pregnancy. However, the current analysis finds that the condition x trimester interaction was significant such that, in the weighted condition, controls displayed a

greater arch height index than the pregnant women in their first two trimesters and postpartum; first trimester participants displayed a greater arch height index than in the second and third trimesters and post-partum, and the third trimester values were greater than when the women were in their second trimester. We do not know what effect, if any, swelling had on our results. Swelling is very common, as more than eighty-five percent of women report swelling of the lower leg and foot during pregnancy (9). The incidence and magnitude of lower leg edema peaks in the third trimester (28). It may be that in their third trimesters, the feet of the pregnant women were swollen enough so that the dorsal height of the midfoot read higher on the AHIMS, thus reading as a higher arch. Perhaps the fact that the arch height index was lower in the weighted condition in the first and second trimesters and post-partum when compared to the third trimester condition was that swelling gave the foot more height, and this not seen in the other time points in pregnancy. Because no differences were noted between pregnancy trimesters in the natural condition (21), it could be that it took the additional weight to lower the arch in the other trimesters, but the arch could not get lower in the third trimester because of the swelling on the plantar aspect of the foot.

We could not assess any viscoelastic effects of the influence of added weight over a period of time, as in a real-life pregnancy that lasts nine months. Rather, we examined the short-term effects of adding a weight for a portion of the data collection session. The average pregnant participant in our study gained 16.2 ± 6.3 kg by her third trimester visit. It would not be feasible to continually add this amount of weight over the course of nine months to a non-pregnant study participant to determine the effects of added weight alone. This is a limitation of the study.

Our small sample size of 15 pregnant women and 13 nulligravida women is a limitation of the study. With this small number, we may not be able to accurately detect small, medium, or large between-group effects. Given the small sample size and our limited ability to detect effect sizes, some small group differences of 1% or 0.5mm that were statistically significant may not be clinically meaningful.

A further limitation of this study is that the pregnant participants were significantly older than the non-pregnant group. It was not feasible to match on age, as more than 80% of women have been pregnant by age 50, thus finding nulliparous women in that age group is difficult. However, previous work has demonstrated that there is no relationship between age and arch height or stiffness (29). Thus, we do not expect that the five year age difference between groups had a strong influence on our results.

Finally, these results are only generalizable to primigravida women. Segal et al. (14) reported that the greatest changes in arch height and rigidity occur during a first pregnancy. Thus it is likely that changes occurring during the first pregnancy persist, and thereafter there is little room for the arch to drop further.

It should be noted that our pregnant participants in this cohort reported little or no pain on a questionnaire asking them to rate their pain in the lumbar spine, posterior pelvis, and foot on a visual analogue scale over the course of their pregnancies (21). Given that fifty-six percent of pregnant women report lower leg and foot pain (20), and that this pain may be related to changes in foot anthropometry, it is feasible that our study examined a cohort with minimal foot alterations. Women who report significant pain may also develop more severe foot alterations and dysfunction as a result of the pregnancy. We are currently collecting data on the

relationship of development of these anthropometric alterations to self-reported pain in pregnant women in their third trimester who report significant pain.

By the age of 50, more than 80% of American women have experienced at least one pregnancy (30). More than half of women report leg and foot pain during a pregnancy (9), with the incidence of pain increasing with the number of pregnancies (31). Pregnancy leads to long-term changes to foot structure and function, and these changes may be related to the incidence of pain (10, 14, 32). Thus, prevention of these physical changes to foot anthropometry may be of clinical concern. While we realize that we will not be able to, nor should we try to, alter serum hormone concentrations in pregnancy, it is important for us to understand the differential contribution of maternal weight gain and pregnancy related-hormones to changes to foot anthropometry and consequential pain so that we may be better able to prevent the pain. Additionally, an understanding that the interaction of weight gain and pregnancy hormones results in different variations of foot shape alterations than just weight gain alone will be valuable in prevention of long-term dysfunction and pain post-partum. For example, it would be beneficial to know if all pregnant women, or only those who have large weight gain during pregnancy, should be instructed to wear shoes with arch support or even prescribed orthotics. While the effect of orthotics on pain has not been evaluated in pregnant women, orthotics are known to reduce risk and severity of lower extremity pain and injury in other adult populations (33–35). Also, it would not be expected that pregnant women would experience the same changes to foot anthropometry that occur with load carriage or obesity, given that the interaction of pregnancy hormones and added weight results in different changes to foot dimensions than just added weight alone. The current results suggest clinicians should consider the additive effect of weight and pregnancy status when evaluating and treating changes in foot anthropometry in pregnant women.

Conclusions

The combination of the increased bodyweight associated with pregnancy and the increased concentration of serum relaxin are related to anthropometric alterations to the feet of pregnant women. Added weight alone resulted in increased arch drop and a decreased arch rigidity index. The interaction of added weight and trimester resulted in increased foot length and width, as well as a lower medial longitudinal arch, as indicated by the arch index and arch height index measures. These alterations persist post-partum, and are likely related to life-long foot pain in women who have experienced a pregnancy, which is a majority of the female population. Thus, this pain is of significant concern. An understanding of the differential contributions of the pregnancy related hormones and increased bodyweight may better enable clinicians to prevent and/or treat this pain.

References

- 1.Nyska M, Sofer D, Porat A, Howard CB, Levi A, Meizner I. Planter foot pressures in pregnant women. *Isr J Med Sci* 1997 Feb;33(2):139–46.
- 2.Ritchie JR. Orthopedic considerations during pregnancy. *Clin Obstet Gynecol* 2003 Jun;46(2):456–66.

- 3.Moore K, Dumas GA, Reid JG. Postural changes associated with pregnancy and their relationship with low-back pain. *Clin Biomech (Bristol, Avon)* 1990 Aug;5(3):169–74.
- 4.Bullock-Saxton J. Changes in posture associated with pregnancy and the early post-natal period measured in standing. *Physiother Theory Pract* 1991;7(2):103–9.
- 5.Fast A, Weiss L, Ducommun EJ, Medina E, Butler JG. Low-back pain in pregnancy. Abdominal muscles, sit-up performance, and back pain. *Spine (Phila Pa 1976)* 1990 Jan;15(1):28–30.
- 6.MacLennan AH, Nicolson R, Green RC. Serum relaxin in pregnancy. *Lancet* 1986 Aug 02;2(8501):241–3.
- 7.Anselmo DS, Love E, Tango DN, Robinson L. Musculoskeletal Effects of Pregnancy on the Lower Extremity: A Literature Review. *J Am Podiatr Med Assoc* 2017 Jan;107(1):60–4.
- 8.Marnach ML, Ramin KD, Ramsey PS, Song SW, Stensland JJ, An KN. Characterization of the relationship between joint laxity and maternal hormones in pregnancy. *Obstet Gynecol* 2003 Feb;101(2):331–5.
- 9.Ponnnapula P, Boberg JS. Lower extremity changes experienced during pregnancy. *J Foot Ankle Surg* 2010 Sep-Oct;49(5):452–8.
- 10.Segal NA, Eagles M. The effects of pregnancy on shoe size and knee laxity. *Am J Phys Med Rehabil* 2010;89:S41.
- 11.Wetz HH, Hentschel J, Drerup B, Kiesel L, Osada N, Veltmann U. Changes in shape and size of the foot during pregnancy. *Orthopade* 2006 Nov;35(11):1124, 6–30.
- 12.Alvarez R, Stokes IA, Asprinio DE, Trevino S, Braun T. Dimensional changes of the feet in pregnancy. *J Bone Joint Surg Am* 1988 Feb;70(2):271–4.
- 13.Block RA, Hess LA, Timpano EV, Serlo C. Physiologic changes in the foot during pregnancy. *J Am Podiatr Med Assoc* 1985 Jun;75(6):297–9.
- 14.Segal NA, Boyer ER, Teran-Yengle P, Glass NA, Hillstrom HJ, Yack HJ. Pregnancy leads to lasting changes in foot structure. *Am J Phys Med Rehabil* 2013 Mar;92(3):232–40.
- 15.Barati AH, Bagheri A, Azimi R, Darchini MA, Nik HN. Comparison balance and footprint parameters in normal and overweight children. *Int J Prev Med* 2013 Apr;4(Suppl 1):S92–7.
- 16.Hills AP, Hennig EM, McDonald M, Bar-Or O. Plantar pressure differences between obese and non-obese adults: a biomechanical analysis. *Int J Obes Relat Metab Disord* 2001 Nov;25(11):1674–9.
- 17.Tsung BY, Zhang M, Fan YB, Boone DA. Quantitative comparison of plantar foot shapes under different weight-bearing conditions. *J Rehabil Res Dev* 2003 Nov-Dec;40(6):517–26.
- 18.Wearing SC, Hennig EM, Byrne NM, Steele JR, Hills AP. Musculoskeletal disorders associated with obesity: a biomechanical perspective. *Obes Rev* 2006 Aug;7(3):239–50.

19. Marieb E, Mallatt J, Wilhelm P. Chapter 9: Joints. San Francisco, CA: Pearson Benjamin Cummings; 2005.
20. Vullo VJ, Richardson JK, Hurvitz EA. Hip, knee, and foot pain during pregnancy and the postpartum period. *J Fam Pract* 1996 Jul;43(1):63–8.
21. Harrison KD, Mancinelli C, Thomas K, Meszaros P, McCrory JL. The relationship between lower extremity alignment and back and lower extremity pain during pregnancy: a longitudinal study of primigravid women vs. nulliparous controls. *Journal of Womens Health Physical Therapy* 2016;40(3):139–46.
22. Cavanagh PR, Rodgers MM. The arch index: a useful measure from footprints. *J Biomech* 1987;20(5):547–51.
23. Wong CK, Weil R, de Boer E. Standardizing foot-type classification using arch index values. *Physiother Can* 2012 Summer;64(3):280–3.
24. Pohl MB, Farr L. A comparison of foot arch measurement reliability using both digital photography and calliper methods. *J Foot Ankle Res* 2010;3:14.
25. Williams DS, McClay IS. Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. *Phys Ther* 2000 Sep;80(9):864–71.
26. McCrory JL, Chambers AJ, Daftary A, Redfern MS. The pregnant “waddle”: an evaluation of torso kinematics in pregnancy. *J Biomech* 2014 Sep 22;47(12):2964–8.
27. <http://mayoclinic.org>. Labor and delivery, Post-partum care. Mayo Clinic; 2017.
28. Smyth R, Aflaifel N, Bamigboye A. Interventions for varicose veins and leg oedema in pregnancy. *Cochrane Database System Reviews* 2015;19(10).
29. Zifchock RA, Davis I, Hillstrom H, Song J. The effect of gender, age, and lateral dominance on arch height and arch stiffness. *Foot Ankle Int* 2006 May;27(5):367–72.
30. Bureau of the Census for the Bureau of Labor Statistics: Current Population Survey. 2011.
31. Ostgaard H, Andersson G, Karlsson K. Regression of back and posterior pelvic pain after pregnancy. *Spine (Phila Pa 1976)* 1996;21(23):2777–80.
32. Casto E, Mancinelli C, Meszaros P, Boyer K, McCrory J. The Relationship Between Lower Extremity Asymmetries and Low Back and Lower Extremity Pain with Pregnancy. New England Regional Meeting of the American College of Sports Medicine; 2016 October 14–16, 2016; Providence, RI
33. Bonacci J, Hall M, Saunders N, Vicenzino B. Gait retraining versus foot orthoses for patellofemoral pain: a pilot randomised clinical trial. *J Sci Med Sport* 2017 Oct 2.
34. Bonanno DR, Landorf KB, Munteanu SE, Murley GS, Menz HB. Effectiveness of foot orthoses and shock-absorbing insoles for the prevention of injury: a systematic review and meta-analysis. *Br J Sports Med* 2017 Jan;51(2):86–96.

35.Molgaard CM, Rathleff MS, Andreasen J, Christensen M, Lundbye-Christensen S, Simonsen O, et al. Foot exercises and foot orthoses are more effective than knee focused exercises in individuals with patellofemoral pain. *J Sci Med Sport* 2017 Jan;21(1):10–5.

Declarations

- Ethics approval and consent to participate

This study was approved by the WVU Institutional Review Board. [Protocol reference number: H-23586] Approved under the title: "Relationship between changes in foot and pelvis alignment and the incidence of lumbar, posterior pelvis, and foot pain during pregnancy." All study participants provided informed consent prior to their participation in the study.

- Consent for publication

Not applicable. This manuscript does not contain data from any one individual person.

- Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

- Competing Interests

The authors declare that they have no competing interests.

- Funding

This study was not funded.

- Authors' contributions

KDH: This study was KDH's Masters thesis. As such, she participated in all aspects of this study, from study design, subject recruitment, data collection, data analysis, statistical analysis, data interpretation, and manuscript preparation.

KT: KT is a physical therapist who is a certified Women's Health Specialist. The idea behind the study came from KT's clinical experience and expertise. She participated in study design, data interpretation, and manuscript preparation.

CM: CM is a physical therapist with strong clinical experience in orthopedics. She participated in study design, data analysis, data interpretation, and manuscript preparation.

PM: PM is an OBGYN physician. She was integral in subject recruitment for the pregnant women in the study. She participated in study design, subject recruitment, data interpretation, and manuscript preparation.

JLM: JLM was KDH's MS advisor. She participated in most aspects of this study, including study design, data collection, data analysis, statistical analysis, data interpretation, and manuscript preparation.

All authors read and approved the final manuscript.

- Acknowledgements

We would like to acknowledge the contribution of Peter Cavanagh, PhD, to the design of this study.

- Authors Information

Several of the authors are no longer at West Virginia University. Addresses on the cover page reflect their positions during their participation in this study. Their current addresses are as follows:

Kathryn D. Harrison, MS: Department of Kinesiology and Health Sciences, Virginia Commonwealth University, Richmond, VA 23284 Email: harrisonkathryn89@gmail.com

Krystal Thomas, DPT, MS: Ballad Health Homecare in Abingdon, VA 24210 Email: ktwvupt@gmail.com

Corrie Mancinelli, PhD, PT: Same as stated on cover page

Petronela Meszaros, MD: Atria Health, Charlotte, NC 28207 Email: petronela65@hotmail.com

Jean L. McCrory, PhD: Same as stated on cover page

Tables

Table 1: Subject demographics (mean \pm standard deviation)

	Age (yrs)	Height (cm)	Mass (kg)	Weeks Pregnant/ Post-partum
Control	22.0 \pm 1.5	164.0 \pm 4.6	62.0 \pm 7.7	0
Pregnant	29.0 \pm 3.6*	167.7 \pm 6.4	63.0 \pm 8.8 (pre-pregnancy)	
1 st Trimester			62.7 \pm 8.8	10.8 \pm 2.2*
2 nd Trimester			73.1 \pm 11.9*	25.0 \pm 2.0*
3 rd Trimester			79.6 \pm 13.5*	36.1 \pm 1.1*
Post partum			68.5 \pm 14.2	7.9 \pm 2.9

* Denotes significant difference from the control group ($p < 0.05$).

Table 2: Foot anthropometric variables in natural and weighted conditions (mean \pm standard deviation).

		Control	1 st Trimester	2 nd Trimester	3 rd Trimester*	Post-partum
Foot length (cm)	Natural	23.8±0.8	24.4±1.0	24.5±1.1	24.6±1.3 ^a	24.6±1.1
	Weighted	23.8±0.8 ^{bcd e}	24.5±0.9	24.5±1.2 ^a		24.7±1.1 ^a
Foot width (cm)	Natural	8.9±0.7	9.2±0.7	9.3±0.7	9.2±0.8 ^{ae}	9.3±0.7
	Weighted	8.9±0.7 ^{cde}	9.1±0.7 ^e	9.3±0.7 ^a		9.4±0.7 ^{abd}
Arch Index	Natural	0.23±0.06	0.23±0.06	0.25±0.04	0.26±0.03 ^a	0.25±0.04
	Weighted	0.23±0.06 ^{cde}	0.24±0.05	0.26±0.04 ^a		0.26±0.04 ^a
Standing Arch Height Index	Natural	0.33±0.02	0.31±0.02	0.32±0.02	0.33±0.03 _{bce}	0.32±0.03
	Weighted	0.33±0.02 ^{bce}	0.30±0.01 ^{acde}	0.32±0.02 ^{abd}		0.32±0.03 ^{abd}
Arch Drop (cm)†	Natural	0.36±0.15	0.37±0.12	0.39±0.13	0.46±0.15	0.41±0.16
	Weighted	0.44±0.15 ^e	0.49±0.12	0.43±0.14		0.49±0.17 ^a
Arch Rigidity Index†	Natural	0.92±0.03	0.92±0.03	0.92±0.02	0.91±0.03	0.92±0.03
	Weighted	0.92±0.04	0.90±0.03	0.92±0.03		0.90±0.03

* 3rd trimester participants are at their maximum weight, so they are both “natural” and “weighted”.

† denotes significant difference between natural and weighted

^asignificant difference from controls

^bsignificant difference from 1st trimester weighted

^csignificant difference from 2nd trimester weighted

^dsignificant difference from 3rd trimester

^esignificant difference from post-partum weighted