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**BIOMEDICAL ENGINEERING | RESEARCH ARTICLE**

# Dynamic plantar pressure and ground reaction force during pregnancy: A prospective longitudinal study

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**Abstract:** **Purpose**: The purpose of this study was to investigate the changes in dynamic plantar foot pressure distribution and vertical ground reaction force in normal pregnant women at their three different trimesters.
**Participants and methods**: Nineteen normal primigravida pregnant women in their first trimester. Participants completed three trials across the plate walkway.
**Outcomes Measures**: The primary outcome was the peak plantar foot pressure distribution under the big toe, first and fifth metatarsal heads, the heel while the secondary outcome was vertical ground reaction force normalized to the units of body weight. There were measured by RS Foot Scan in three different trimesters of pregnancy for both feet.
**Results**: Repeated-measures analysis of variance showed a significant increase ($P < 0.05$) in the plantar foot pressures under heel, first and fifth metatarsal heads, and big toe between first and either second or third trimesters as well as between second and third trimesters of pregnancy for all areas except heel

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## PUBLIC INTEREST STATEMENT

During pregnancy, feet tend to swell because of the increased body weight,which causes extra stress, discomfort, and pain for Mom as a side effect especially at her feet and often forces women to "accommodate" their gait to fit their situation. If foot pain is more serious, a pair of cushioned insoles can help support the feet and relieve pressure points. Shoe inserts may be needed to relieve pressure and stabilize abnormal motion or joints that may be giving way. So, this study will help the pregnant woman to choose a comfortable shoe which can be helpful for her.not

at both feet. Additionally, there was a significant increase in the first peak of vertical ground reaction force normalized to the units of body weight between first and third trimesters as well as between second and third trimesters at both feet. There was a significant increase in the second peak of vertical ground reaction force normalized to the units of body weight between first and either second or third trimesters at both feet.
**Conclusion**: Pregnancy is accompanied by changes in both dynamic plantar pressure distribution and vertical ground reaction force normalized to the units of body weight.

**Subjects: Biomechanics; Biomechanics and Human Movement Science; Medicine; Allied Health; Midwifery**

**Keywords: foot kinetics; plantar foot pressure; foot scan; plate system; pregnant women**

## 1. Introduction

During pregnancy, women undergo numerous hormonal and anatomical changes (Ireland & Ott, 2000). As a part of the anatomical changes, the musculoskeletal system undergoes a series of ligament, joint, and postural modifications that can result in painful discomfort in the musculoskeletal system (Ritchie & Joseph, 2003). In turn, changes body weight and foot biomechanics that occur with changes in the foot structure have been reported during pregnancy (Ribas & Guirro, 2007). During pregnancy, body weight increases extensively and is mainly focused on the anterior lower trunk. Due to natural weight gain during this period, a woman's center of gravity is altered. The distribution of weight in the body alters as the fetus enlarges causing the center of gravity to deviate ventrally (Ribas & Guirro, 2007). Feet, which act as the body's base of support, endure ground reaction forces during daily activities. Pregnant women may be at an increased risk of developing foot discomfort and/or foot pathologies due to increased plantar loads (Fan, Qianxiang, Zhongqi, Lijun, & Yushuang, 2015).

The effect of increased body mass on plantar pressure has been studied in both adults and children extensively by Yan, Zhang, Tan, Yang, and Liu (2013). The authors found that plantar pressures under the metatarsal head II-V, midfoot and heel lateral were significantly higher for obese than non-obese subjects. They concluded that obese children have weaker walking stability with flatter foot pattern, the larger foot axis angle and dynamic plantar pressure distribution changes compared to non-obese children. Additionally, Hills, Hennig, McDonald, and Bar-Or (2001) examined plantar pressure differences between non-obese and obese adults during standing and walking using a pressure distribution platform. The authors revealed that obese subjects higher plantar pressures and increased forefoot width during walking and standing in compared to a non-obese group.

Pregnancy is a physiological state marked by an increase in body mass; it is, however, likely that foot pressure distribution is affected differently than in obesity as previously stated by Ochsenbein-Kölble, Roos, Gasser, and Zimmermann (2007). Several studies have already been published on this topic. One of these studies noted that peak pressure under the lateral forefoot and midfoot regions increased in the third trimester compared to the first trimester and claimed that loading under the toes was transferred to the big toe from the first to the third trimester (Lymbery & Gilleard, 2005). Others found that forefoot pressure increased in the third trimester of pregnancy during standing and walking (Karadag-Saygi, Unlu-Ozkan, & Basgul, 2010). Moreover, it was found that peak pressure and maximum force of the medial rearfoot reduced from the first to third and second to third trimesters; and maximum force increased at the medial forefoot from the first to the second trimester (Ribeiro et al., 2011). In contrast, some researchers revealed that peak pressure increased in rearfoot and decreased in forefoot during walking as pregnancy progressed

(Nyska et al., 1997). To date, it still remains controversial how loads on plantar surface change throughout pregnancy in gait (Lymbery & Gilleard, 2005). During walking, loads over the plantar surface change progressively as body mass is increasing, the center of gravity is moving forward, and orthostatic posture is changing throughout gestational ages. A better understanding of these biomechanical adjustments would result in more appropriate prophylactic treatment of foot pain symptoms in pregnant women (Nyska et al., 1997). Therefore, the purpose of this study is to investigate the changes of dynamic plantar foot pressure distribution and vertical ground reaction force normalized to the units of body weight in normal pregnant women at their three different trimesters.

## 2. Methods

### *2.1. Participants*

A convenient sample of 19 normal primigravida pregnant women in their first trimester (less than 12 weeks of pregnancy) participated in this study. They were enrolled and assessed for their eligibility to participate in the study. To be included in the study, participants must have an age range from 20 to 35 years old, their height must range from 155 to 169 cm, it should be their first pregnancy (primigravida), their body mass index (calculated as weight in kilograms divided by the square of height in meters) should be less than 30, and lastly their weight gain must be smaller than 12 kg throughout gestation (gestational age of each pregnant woman was calculated starting from the first day of last menstrual cycle plus 9 months and another 7 days). Gestational age was confirmed by ultrasonography. The participants were excluded if they had diabetes, pre-eclampsia, varicose veins, low back pain, sacroiliac joint pain, symphyseal joint pain, twin's pregnancy, claudication (leg cramping); deformities and/or previous surgeries at their back and lower limbs. A total of 23 pregnant women were eligible for inclusion, but only 19 completed the trials and had their data analyzed. Four pregnant women did not meet the inclusion criteria. The body mass in the first, second and third trimesters of the pregnant women ranged from 59 to 78 kg, 63 to 83 kg and 67 to 88 kg, respectively. The mean body mass was 68.05 ± 6.9 kg in the first trimester, 72.83 ± 9.8 kg in the second trimester, and 77.38 ± 7.5 kg in the third trimester. It represented an increase of 9.33 kg between first and third trimester. Participants were recruited from the Outpatient Clinic of antenatal care at Kasr El-Aini University Hospital, Faculty of Medicine, and measured in the motion analysis lab, Faculty of Physical Therapy, Cairo University, Egypt. The study was conducted between June 2014 and August 2016. The informed consent form was signed by all participants, and the study was approved by the Research Ethical Committee of the Faculty of Physical Therapy, Cairo University before study commencement. The study was designed as a prospective, observational, longitudinal, cohort study and followed the Guidelines of Declaration of Helsinki on the conduct of human research.

### *2.2. Outcome measures*

The primary outcome was the peak plantar foot pressure distribution under the big toe, first and fifth metatarsal heads, and the heel. The secondary outcome was vertical ground reaction force normalized to the units of body weight. This was measured by RS Foot Scan International Plate System (Lammerdries oost 27, B-2250 Olen) with a sampling rate of 300 Hz and a resolution of 4 sensors per $cm^2$ in the first, second and third trimesters of pregnancy for both feet. The data were exported to the foot scan (RS) software as measured with the force scan (R) plate. Therefore, dynamic plantar foot pressure distribution can be measured.

### *2.3. Data measurement*

Ultrasonography was conducted by the physician to calculate the gestational age of each pregnant woman as well as to exclude any congenital anomalies, hydramnios, and twins of fetuses. History was taken from each pregnant woman before starting the study. Height was recorded while weight was repeatedly measured before starting each measurement at the first, second and third trimesters of pregnancy. Each participant was instructed carefully about the evaluative procedures and was advised to empty their bladder and apply the test barefoot. The foot scan device was calibrated before starting the plantar foot pressure measurement. The physical therapist recorded the demographic data of each assessed pregnant woman on the computer including body mass (Kg) and shoe size (UK), which are important in the calibration of the measurements and saved the data in the software of the system.

For familiarization purposes, participants completed 1–2 practice trials across the plate walkway to ensure that they were comfortable with the experimental procedure. Participants were asked to walk from a “start point” to a “finish line” at their normal or comfortable speed. The start point was approximately six steps in front of the foot scan platform, and the stop point was four steps behind the plate. The participants were allowed to rest if they felt tired between trials for at least 2 min. A trial was considered valid when the woman hit the plate with one foot and was fully on the plate. Then, she returned to her starting position and repeated the previous steps, but hit the force plate this time with her other foot. This plantar pressure plate has an area of 0.578 m x 0.418 m with 4096 resistive sensors, resulting in a resolution of 4 sensors per $cm^2$. The platform was covered with a top layer made from EVA material (hardness: Shore A70) to prevent the subjects from adjusting their walking style and aiming at the plate (Fan et al., 2015; Yan et al., 2013). Mean values of three valid trials from each foot were analyzed. For each trial, the participant’s right and a left foot strike was measured on the plate. Evaluation of each pregnant woman was conducted three times: first (at 12 weeks), second (at 24 weeks), and third (at 36 weeks) of trimester’s pregnancy.

### *2.4. Data processing*
The data of each pregnant woman were processed and edited into the Foot scan (RS) software in which both feet images were generated. The images were compound images from all maximum pressures as measured during the stance phase as well as the vertical ground reaction curve. The foot axis was plotted accurately on the middle heel through the second metatarsal bone. Hence, all numerical data were calculated in comparison to this foot axis. Then, the pressure distribution under the studied anatomical landmarks (big toe, the first and fifth metatarsal heads and the heel) was measured for both feet. The peak pressure distribution represents the maximum pressure detected by each sensor during the stance phase of gait and is a function of the amount of force (in newton) maintained through a defined area (in centimeters squared) of the foot. The ground reaction force is another outcome that can be measured by the foot scan device, and in this study, vertical ground reaction force normalized to the units of body weight’s first and second peaks were calculated.

### *2.5. Study size*
Power analysis was conducted in G*Power. Running a power analysis on a repeated measures ANOVA with three measurements, a power of 0.80, an alpha level of 0.05, and a large effect size ($f = .42$) (Faul, Erdfelder, Buchner, & Lang, 2013). The required sample size is 12. To account for dropout rates, the sample size was increased to 19.

### *2.6. Data analysis*
Data were analyzed using the Statistical Package for Social Sciences version 20 (SPSS Inc., Chicago, IL, USA). Preliminary assumption checking revealed that data was normally distributed, as assessed by Shapiro–Wilk test ($p > .05$); there were no univariate, as assessed by a boxplot. Mauchly’s test of sphericity was measured and indicated that the assumption of sphericity was met. All these findings allowed the researchers to conduct the parametric analysis. So, repeated measure analysis of variance (ANOVA) test was used for analysis of the foot pressure distribution under the heel, the first metatarsal head, the big toe, the fifth metatarsal head, and ground reaction forces (first and second vertical peak) for both legs. Multiple pairwise comparison tests (Post hoc tests) was used to determine the difference among three trimesters if the within-subject (ANOVA) test showed significant results. The level of significance was set at 0.05 for all statistical results.

## 3. Results

Regarding the foot pressure and ground reaction forces (first and second vertical peak), there were significant changes in the peak pressure distribution under both heels, the first metatarsal head, the big toe, the fifth metatarsal head, and lastly in the first and second peaks of vertical GRF. There were significant differences among three trimesters regarding the right heel (F = 16.88, $p < .001$), the left heel (F = 15.98, $p < .001$), the right first metatarsal head (F = 13.6, $p < .001$), and the left first metatarsal head (F = 13.3, $p < .001$). As well as, there were significant differences among three trimesters concerning the right big toe (F = 37.25, $p < .001$) whereas the left big (F = 36.85, $p < .001$), the right and left fifth metatarsal heads (F = 5.5, $p = .008$), and (F = 4.6, $p = .006$), respectively. Moreover, there were significant differences among three trimesters for first peak of vertical GRF at the right foot (F = 2.7, $p < .001$) and the left foot (F = 2.5, $p < .001$) respectively, and the second vertical GRF for the right and left feet (F = 2.7, $p < .001$) and (F = 2.5, $p < .001$) respectively, as shown in (Table 1).

The post hoc test for the first and second evaluation (first and second trimester) showed a significant increase in foot pressure under the heel (p = .001) for both legs, under the first metatarsal head ($p < .001$) at both legs, under the big toe ($p < .001$) at both legs, and under the fifth metatarsal head ($p < .001$) at both legs. However, it showed no significant changes in first peak of vertical GRF ($p = .75$) for the right leg and ($p = .69$) for the left leg, but there was a significant increase in the second peak of vertical GRF ($p = .01$) at both legs.

Between the second and third trimesters, there was a significant increase in foot pressure under the first metatarsal head ($p < .001$) for both legs, under the big toe ($p = .005$) for right leg and ($p = .004$) for left leg, under the fifth metatarsal head ($p < .001$) for both legs, and significant increase in first peak of vertical GRF ($p = .01$) for both legs. However, there were no significant changes in foot pressure under the heel: ($p = .18$) for the right leg ($p = .15$) for the left leg ($p = .17$) second peak of vertical GRF for the right leg, and ($p = .16$) for the left leg.

Comparing the first trimester to the third trimester, the pregnant women showed significant increase in foot pressure under the heel ($p < .001$) for both legs, under the first metatarsal head

**Table 1. Dependent variables obtained from the pregnant women in the first, second, and third trimesters of normal pregnancy at right and left legs.**

| Dependent variables | Leg side | 1st trimester | 2nd trimester | 3rd trimester |
|---|---|---|---|---|
| Peak pressure under the heel ($N/cm^2$) | R | 39.95 ± 6.48 | 43.25 ± 7.8* | 46.61 ± 10.5¥ |
| | L | 39.5 ± 6.2 | 42.25 ± 6.8* | 45.61 ± 10.3¥ |
| Peak pressure under the 1st metatarsal head ($N/Cm^2$) | R | 18.91 ± 8.0 | 20.65 ± 7.80* | 21.71 ± 7.3#¥ |
| | L | 18.01 ± 7.95 | 20.15 ± 7.60* | 20.99 ± 6.98#¥ |
| Peak pressure under the big toe (N/Cm2) | R | 25.01 ± 8.76 | 26.39 ± 8.99* | 27.9 ± 9.28#¥ |
| | L | 24.91 ± 8.67 | 25.99 ± 8.08* | 27.02 ± 9.08#¥ |
| Peak pressure under the 5th metatarsal head (N/Cm2) | R | 10.13 ± 3.49 | 11.52 ± 5.07* | 13.07 ± 3.49#¥ |
| | L | 9.96 ± 3.94 | 10.92 ± 4.97* | 12.97 ± 3.19#¥ |
| The 1st peak of normalized vertical GRF to body weight | R | 0.70 ± 0.13 | 0.66 ± 0.09 | 0.63 ± 0.13#¥ |
| | L | 0.69 ± 0.13 | 0.65 ± 0.09 | 0.62 ± 0.13#¥ |
| The 2nd peak of normalized vertical GRF to body weight | R | 0.71 ± 0.16 | 0.67 ± 0.12* | 0.64 ± 0.15¥ |
| | L | 0.70 ± 0.16 | 0.66 ± 0.11* | 0.63 ± 0.15¥ |

*significant ($p < .05$) difference between 1st trimester and 2nd trimester, #significant ($p < .05$) difference between 2nd trimester and 3rd trimester, ¥significant ($p < 0.05$) difference between 1st trimester and 3rd trimester.

($p < .005$) for the right leg, and ($p < .006$) for the left leg, under the big toe ($p < .005$), for the left leg ($p = .006$), under the fifth metatarsal head ($p < .001$) for both legs, first peak of vertical GRF ($p = .01$) for both legs, and second peak of vertical GRF ($p = .01$) for both legs. Moreover, there were no significant changes in the foot pressure and ground reaction forces at first, second and third trimesters of normal pregnancy between both legs ($p > .05$).

## 4. Discussion

Understanding the biomechanics of gait during different pregnancy phases is of great importance. It allows prescribing suitable exercises for women in this critical time of their life. Rehabilitation programs are considered to be helpful in order to adjust pregnant women's ability to adapt to the postural deviations resulting from pregnancy and protect her from musculoskeletal injuries.

### *4.1. Dynamic plantar pressure distribution*

The results of this study revealed a significantly high statistic increase in the weight of the pregnant woman between the three trimesters of pregnancy. There was a gradual increase between the first and second trimester (around 4 kg) and between the second and third trimester (around 5 kg). This was both expected and supported by the result of a study that concluded that women had a mass gain within the recommended range (10.49 ± 1.59 kg) throughout their pregnancy (Moccellin, Nora, Costa, & Driusso, 2015). The physiological changes of the enlargement of the uterus, an increase in fetus and breasts size, increase in water retention and an increase in plasma volume (50–60%) by the end of third trimester may all contribute to the increase in weight (Soma-Pillay, Nelson-Piercy, Tolppanen, & Mebazaa, 2016).

The present study showed that there was no significant difference between the right and left feet for both pressure distribution and vertical ground reaction force normalized to the units of body weight during the dynamic test. Our results were supported by many studies in assessing static foot pressure distribution by using the foil pedobarograph (Grieve & Rashdi, 1984). For instance, some researchers have found no significant differences between both feet in vertical GRF during gait (Došla et al., 2013). Additionally, it was stated that in static standing, foot pressure distribution had a significant difference between both sides in forefoot and midfoot, while in dynamic situation there was a significant difference between both sides in midfoot only, but no significant difference in total pressure between the dominant and non-dominant side (Imamura et al., 2002).

The results of the present study revealed a highly significant statistical increase in the dynamic pressure distribution under the big toe, first metatarsal, and fifth metatarsal between the first and either second or third trimesters and between second and third trimester. However, under the heel, the change was found to be only statistically significant between the first and second and first and third trimesters of pregnancy. This result indicates that the pressure distribution over the different points of the foot increased significantly from trimester to another except for the heel, since there was no significant increase between the second and third trimesters.

In contrast, another study concluded that there was no change in the peak plantar pressure between the different trimesters, opposing the results of this study (Ribas & Guirro, 2007). Many studies concerned with assessing postural control in pregnant women through the center of pressure (COP) and center of gravity (COG) displacement had different results. Moccellin and Driusso (2012) revealed that pregnant women had higher COP displacement in the first trimester in comparison to control group and other trimesters, with higher instability in the first trimester.

In accordance, Opala-Berdzik, Bacik, Cieślińska-Świder, Plewa, and Gajewska (2010) found that a vertical projection of COG was displaced posteriorly in pregnant women in comparison to non-pregnant. In addition, Nyska et al. (1997) revealed that pressure foot distribution was higher in static measurement under the hind foot in pregnant women in comparison to non-pregnant, whereas during dynamic assessment peak, pressure was higher on midfoot. The disagreement may be due to the individual variation between women physiological responses, their activities and how the posture responds to it (Neumann, 2010).

### 4.2. Vertical GRF

The present study showed no significant changes in first peak of vertical GRF in both legs between the first and second trimester. However, there were significant changes between both second and third trimesters and also between first and third trimesters. For the second vertical peak of the GRF, there was a significant difference between first and second trimester and between first and third trimester but no difference between second and third trimester.

GRFs have two peaks through the gait cycle, the first peak is at the time of the loading response, and the second peak is at the time of terminal stance. It resulted from the vertical acceleration of the COG (Yan et al., 2013). Therefore, a vertical GRF should be greater than the body weight to decelerate at loading response (first peak of vertical GRF) and then accelerate upwards during terminal stance (second peak of vertical GRF). High GRF at the terminal stance reflects the push off by the plantar flexors and the required action to reverse the downward movement of the body during this phase (Neumann, 2010).

Goffar et al. (2013) investigated the dynamic pressure during loaded gait and reached the same conclusion concluded by this study and claimed that GRF increased with increasing load. Yang and Zou (2010) generated a simulation model for one stride walking of pregnant women to optimize the changes happening through gait in kinematics and kinetic measures. The study revealed that the vertical GRF increased by increasing the number of months of pregnancy, with no significant difference between right and left foot, which coincides with the present study results.

When analyzing the gait of pregnant women in the second and third trimesters, it was concluded that there was no significant difference between first and second trimesters in initial stance vertical GRF, while there was a significant difference between second and third trimesters in push-off phase vertical GRF (Branco, Santos-Rocha, Aguiar, Vieira, & Veloso, 2016). The significant increase in the second and third trimesters of the second vertical GRF in comparison to first trimester with no change between second and third may be due to the increased time to perform full push off of the stance foot as stated by. This was also concluded in another study which suggested that throughout pregnancy, women adopt certain strategies to maintain their balance during gait (Marques, Gonçalves, Santos, & Vilas Boas, 2005).

In contrast to our results regarding ground reaction force, it was found that there is a significant decrease of GRF peaks with pregnancy, which can be explained as a protective mechanism to keep unchanged loading and decrease shocks or trauma to the fetus (Gimunová et al., 2015). In addition, Santos, Gil, Marques, Vilas Boas, and Silva (2008) compared the GRF during walking in pregnant women in the third trimester of pregnancy with non-pregnant women. They reported a significant increase in GRF in both the right and left foot in the first peak in comparison to non-pregnant women, which agreed with our results. There was an increase in the second peak but only of significant difference in the left foot, the difference between the two feet was different from the present study, and they discussed the difference between the two feet to decrease push-off force that the pregnant woman exerts, which may lead to imbalance during walking.

Lastly, there are some limitations to this study. First, there was no control group of non-pregnant women to determine if there are changes in the first trimester of pregnancy compared with non-pregnant peers. Second, this study examined only plantar pressure distribution at the big toe, first and fifth metatarsal heads, and the heel areas without consideration of midfoot and 2nd–3rd metatarsal heads. Finally, gait speed was not controlled for all participants.

It was concluded that during dynamic conditions, the plantar pressure distribution increased on the forefoot through the three trimesters with insignificant increase under heel from second to third trimester plus an increased GRF during gait, this maldistribution of loads over pregnant women's feet requires great attention for her balance and musculoskeletal complaints These results must be considered by physical therapists to enhance pregnant women's balance through proprioception training programs to reduce risk of fall especially in women with a sedentary lifestyle.

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