

ANALYSIS OF GROUND REACTION FORCES IN THE SECOND AND THIRD TRIMESTERS OF PREGNANCY DURING WALKING

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Brief communication

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Abstract:

The objective of the current study was to examine the effect of pregnancy during the 2nd and 3rd trimesters on ground reaction forces (GRFs). Twenty-four non-pregnant women and forty-eight pregnant women in the second and third trimesters participated in this cross-sectional study. Qualisys Gait Analysis System was used to analyze peaks and time parameters of GRFs in vertical (Fz), antero-posterior (Fy) and medio-lateral directions (Fx). The results showed that there were no significant differences between the non-pregnant and the pregnant women in the first peak (Fz1) ($p=.147$) and the second peak (Fz2) ($p=.125$) of vertical GRF, braking force (FyB) ($p=.867$) and propulsion force (FyP) ($p=.929$), as well as lateral (FxD) ($p=.994$) and medial (FyM) GRF ($p=.920$). However, there was a significant increase in the Fz minimum (min) ($p=.008$), and a decrease in the difference between the Fz1 and Fz min ($p=.042$) and the difference between Fz2 and Fz min ($p=.028$). Moreover, there were increases in the time taken to reach the Fz1 ($p=.024$), Fz2 ($p=.005$), Fz min ($p=.001$), FyB ($p=.010$), FyP ($p=.001$), FxD ($p=.010$) and FyM ($p=.011$). These findings displayed that the pregnant women assumed a flatter pattern of vertical GRF and a decreased downward movement of center of gravity. This pattern may help to make the gait smooth and efficient. Increased time to reach peaks of GRFs may be a strategy to maximize balance during pregnancy.

Key words: *ground reaction forces, pregnancy, walking*

Introduction

The women are subjected to morphological, physiological and hormonal changes during pregnancy, which can lead to compensatory motions in gait. These changes, including increased body weight (Dumas, Reid, Wolfe, Griffin, & McGrath, 1995), lower back extension (Whitcome, Shapiro, & Lieberman, 2007), increased laxity of ligaments (Calguneri, Bird, & Wright, 1982), reduced neuromuscular control and coordination (Wu, et al., 2004), may change some biomechanical parameters such as alterations in mechanical loading and joint kinetics (Foti, Davids, & Bagley, 2000; Gilleard, Crosbie & Smith, 2002; Lymbery, & Gilleard, 2005), decreased abdominal muscle strength (Fernandes da Mota, Pascoal, Carita, & Bø, 2015) and increased spinal lordosis (Dumas, et al., 1995). Increased anterior abdominal mass leads to the relocation of the center of gravity (COG), which leads to the increased lumbar lordosis as a strategy to increase the body balance during pregnancy (Whitcome, et al., 2007).

The increased mass of the trunk during pregnancy may influence the gait variables such as the step time, stance times, double limb support time, maximum hip extension, maximum pelvic right obliquity, pelvic obliquity range of motion, maximum pelvic transversal left rotation and peak hip flexion moments of force (Aguiar, et al., 2015). There is an increase in stride width, hip moment of force, power in the frontal and sagittal planes, maximum ankle plantar flexion force, and maximum ankle plantar flexion power absorption. There is also an increase in the use of the abductor and extensor muscles of the thigh and in the use of the ankle plantar flexor muscles (Foti, et al., 2000).

Pregnancy leads to high fatigability of the lower abdominal muscles that is associated with pelvic girdle pain (Gutke, Östgaard, & Öberg, 2008). More than 50% of pregnant women report hip pain and up to 75% of them complain about back and foot pain (Karadag-Saygi, Unlu-Ozkan, & Basgul, 2010). Muscle fatigability influences the mechanical loading and joint kinetics (Foti, et al.,

2000). Recently, Aguiar et al., (2015) concluded that pregnancy weight gain caused higher biomechanical joint loads during walking compared with the non-pregnant and other women due to carrying a five-kg additional load located in the abdomen.

Braking and propulsive forces of gait are regularly examined by measuring ground reaction forces (GRFs) (Hollman, Brey, Bang, & Kaufman, 2007; White, Agouris, Selbie, & Kirkpatrick, 1999). During walking, GRF is a summation of forces created by body parts (Hollman, et al., 2007). The vertical GRF parameters reflect the symmetrical lower extremity foot loading patterns and show no significant differences between the right and the left limb during normal gait (Došla, et al., 2013; White, et al., 1999). Sadeghi (2003) reported that there were functional differences between the limbs, where one limb was suggested to be more responsible for forward propulsion, while the contralateral limb provided more support and stability, resulting in slight asymmetries of one or several gait variables. Increases in magnitude and variability of the peaks of GRF during weight acceptance and push-off phases are assumed to be found in people with unstable locomotion (Giakas & Baltzopoulos, 1997; Hollman, et al., 2007).

Recently, Gimunová et al. (2015) analyzed changes in vertical GRF across advancing phases of pregnancy. They found a significant decrease in the force of maximal weight acceptance and an increase in main time variables of the step, which were suggested to be a protective mechanism against overloading the contact area of the foot, despite the increase in body mass. There was no significant difference in GRFs or walking speed in women in their third trimesters compared to the postpartum. However, the mediolateral position of the center of pressure (COP) during stance was shifted laterally (Lymbery & Gilleard, 2005). Moreover, McCrory, Chambers, Daftary, and Redfern, (2011) found no differences in the GRFs or COP movement between trimesters or among pregnant fallers and non-fallers.

To our knowledge, most previous studies were longitudinal studies that examined the variations in GRFs between the three trimesters of pregnancy. Also, there is a lack of studies that compared the GRFs characteristics between the pregnant women during different trimesters and the non-pregnant women. Branco, Santos-Rocha, and Vieira (2014) concluded that there were very few studies analyzing the kinetics of gait in pregnant women. Nevertheless, these data are seen as essential to understand the magnitude and implications of changes in the welfare of women. So, this study was conducted to analyze changes in GRFs during the second and the third trimester of pregnancy, by comparing the pregnant to the non-pregnant women. It was hypothesized that the changes in walking mechanics during the second (2nd) and third (3rd) trimesters

of pregnancy would lead to changes in the peaks of GRF during the stance phases.

Methods

Participants

Twenty-four pregnant women in their 2nd trimester (20-22 weeks) and 24 pregnant women in their 3rd trimester (28-32 weeks) were experimental groups (Krkelj, 2018) in this cross-sectional study. A control group consisted of 24 non-pregnant women who were matched to the women of both experimental groups in age, height and weight. It is reported that most of the joint kinetic changes of pregnant women occur between the 2nd and the 3rd trimester of pregnancy (Hamada, Abdel-Aziem, & Youssef, 2016; Lou, et al., 2001). Therefore, the first trimester of pregnancy was excluded. Women were not included in the study if they had diabetes, pre-eclampsia, twins, low back pain, sacroiliac joint pain, symphysis joint pain, deformities and/or previous surgery at their back and lower limbs, neurologic or cardiovascular disorders.

A full instruction about assessment procedures was given to each participant who signed an informed consent form before the study. The study was performed in accordance with the Declaration of Helsinki and approved by the local institutional review board. The demographic data of participants are illustrated in Table 1.

Instrument

Qualisys Gait Analysis System (Qualisys Medical AB, Gothenburg, Sweden) was used to collect kinetic data. It consisted of ProReflex motion capture unit (MCU), an AMTI^b Kistler force plate embedded in the middle of a 10-meter walkway and a personal computer installed with Q Trac and Q Gait software. The MCU unit had six cameras (type170120, 100-240 V, 50-60 HZ, 20 W, 230 MA), which had a capture capability of 120 frames/second.

Procedures

To calibrate the gait analysis system set up, the cameras were placed in suitable positions to view the measurement volume, which covered the full body of the participants. The measurement volume was calibrated using an L-shape wand, which was placed in the middle of the walkway at the force plate with the x-axis in the walking direction. A T-shape wand was moved in the x, y and z directions, so that the wand markers were oriented in all three directions of the measurement volume. It was ensured that all cameras picked up the marker positions in various locations. For calibrating the force plate, four reference markers were placed at the force plate corners; each camera was ensured to pick up the positions of the four markers.

According to the system software, seven markers were used. They were placed on each of the great trochanter, tibial tuberosity, supra patella, midline of the knee, heel, lateral malleolus, and between the 2nd and 3rd metatarsal bone of the right leg (Tranberg, 2010). Each participant was instructed to try out the walkway many times before actual measurement to make sure that the participant would not target the force plate during walking in order to get high quality data. Once the cameras were adjusted at the capturing mode, each participant was asked to walk barefoot along the 10-m walkway three trials at her self-selected speed. The data were processed and edited in the Q-trac software before they were exported to the Q-gait software.

Walking velocity (meter/second) was recorded and GRF kinetic data were collected from the heel contact to the toe-off, which represented one entire gait cycle. GRF components, including vertical GRF (Fz), antero-posterior GRF (Fy) and medio-lateral (Fx) components were measured. GRF magnitude and time parameters were collected. GRF variables included: magnitude of the first maximum peak (Fz1), minimum peak (Fz min) and the second maximum peak (Fz2) of the vertical GRF, braking force (FyB) and propulsion force (FyP) of the antero-posterior GRF, as well as maximum lateral force (FxD) and maximum medial force (FxD) of the medio-lateral GRF (Fx). Moreover, the differences between the peaks of the vertical GRFs were calculated, which included the difference between Fz1 and Fz min (Fz1-Fz min) and the difference between Fz2 and Fz min (Fz2-Fz min).

The Fz1 represented the vertical acceleration of COG that occurred after heel contact, Fz2 represented the upward acceleration of COG that was produced by the activity of the plantar flexors at a push-off, while minimum peak (Fz min) represented the downward acceleration of COG that occurred at mid-stance (local minimum between maximums for the Fz vertical force curve). The braking force (FyB) indicated the horizontal friction between the foot and the floor, while propulsion force (FyP) indicated the forward movement of the body. Maximum lateral force (FxD) indicated the force required to stop medio-lateral velocity of the foot after the heel contact. Maximum medial force (FxD) indicated the force required to decelerate the lateral movement of COG. GRFs were normalized according to the body weight and expressed as a percentage of body weight (Simoneau, 2002). Likewise, the time parameters of GRF were collected. The time taken from heel contact to reach the maximum and minimum peaks were recorded; parameters included the time from heel contact to Fz1 (Fz1 time; the time taken to reach Fz1), Fz2 (Fz2 time; the time taken to reach to Fz2), Fz min (Fz min time; the time taken to reach to Fz min),

FyB (FyB time; the time taken to reach to FyB), FyP (FyP time; the time taken to reach to FyP), FxD (FxD; the time taken to reach to lateral Fx), and FxD (FxD time; the time taken to reach to medial Fx).

Statistical analyses

Data were analyzed by a Statistical Package for Social Sciences (SPSS) version 16.0. Normality test of data was done using the Shapiro-Wilk test that reflected the data were normally distributed for all the dependent variables, which allowed the researchers to conduct a parametric analysis. One-way analysis of variance (ANOVA) was conducted to compare between the vertical force (Fz), antero-posterior force (Fy), medio-lateral force (Fx) and time parameters of the non-pregnant, and the 2nd trimester and the 3rd trimester pregnant women. The level of significance was set at $p < .05$ for all statistical tests with the least significant difference (LSD) used to locate the source of differences.

Results

There was no significant difference between the three groups regarding their age, body height, body weight and BMI ($p = .194$, $p = .747$, $p = .875$, $p = .855$, respectively), as illustrated in Table 1. The average of gestation weeks of the 2nd trimester group was $(21.35 \pm 0.67$ weeks) and that of the 3rd trimester group was $(30.95 \pm 0.83$ weeks).

Regarding the vertical forces Fz1 and Fz2, there were no significant differences between the three groups ($p = .147$, $p = .125$, respectively). The Fz min of the 2nd trimester group and the 3rd trimester group were significantly higher than that of the non-pregnant group ($p = .001$), without significant difference between the 2nd trimester and the 3rd trimester group ($p = .991$). Regarding Fz1-Fz min and Fz2-Fz min, the non-pregnant group scored significantly higher than the 2nd and 3rd trimester groups ($p = .028$, $p = .030$, $p = .039$, $p = .012$, respectively). Moreover, there was no significant difference between the 2nd

Table 1. The participants' demographic characteristics

Groups	Non-pregnant group, n=24	2 nd trimester group, n=24	3 rd trimester group, n=24	ANOVA* p-value
Age (year)	26.63±2.63	25.08±2.99	25.21±3.95	0.194
Height (cm)	161.25±4.57	161.17±4.18	159.54±3.09	0.255
Weight (kg)	68.29±12.83	73.38±9.50	71.54±10.43	0.183
BMI (kg/m ²)	26.29±3.44	28.23±3.33	29.09±3.85	0.115

Note. Data are presented as mean ± standard deviation, *Significance level from ANOVA between the three groups ($p < .05$), BMI: body mass index.

trimester group and 3rd trimester group ($p=.967$, $p=.634$, respectively).

There was no significant difference between the three groups regarding the antero-posterior forces; FyB and FyP ($p=.867$ and $p=.929$, respectively). Moreover, there was no significant difference between the three groups regarding the medio-lateral force; FxL and FxM ($p=.994$ and $p=.920$, respectively), as shown in Table 2.

In relation to the time variables; the Fz1 time and Fz2 time of the 2nd and 3rd trimester groups were significantly higher than that of the non-pregnant group ($p=.010$, $p=.036$, $p=.008$, $p=.003$, respectively), without a significant difference between the 2nd trimester group and the 3rd trimester groups ($p=0.612$ and $p=.700$, respectively). The Fz min time of the 2nd and 3rd trimester groups were significantly higher than that of the non-pregnant group ($p=0.004$ and $p=.012$, respectively), without a significant difference between the 2nd trimester group and 3rd trimester group ($p=.705$).

The FyB time and the FyP time of the 2nd and 3rd trimester groups were significantly higher than that of the non-pregnant group ($p=0.014$, $p=0.005$, $p=0.001$, $p=0.001$, respectively), without a significant difference between the 2nd trimester group and the 3rd trimester group ($p=0.720$, $p=0.968$, respectively). The Fx1 time and Fx2 time of the 2nd trimester and 3rd trimester groups were significantly higher than that of the non-pregnant group ($p=0.042$, $p=0.003$, $p=0.004$, $p=0.032$, respectively), without a significant difference between the 2nd trimester and 3rd trimester groups ($p=0.720$, $p=0.426$, respectively). Regarding walking velocity, there was no significant difference between the three groups ($p=.465$), as shown in Table 3.

Discussion and conclusions

The results of this study showed no changes in the 1st peak (Fz1) and 2nd peak (Fz2) of the pregnant women, which was consistent with the findings of

Table 2. The vertical forces (Fz), antero-posterior force (Fy), and medio-lateral force (Fx) of the non-pregnant, 2nd trimester and 3rd trimester pregnant groups

Forces (N)	Non-pregnant group, n=24	2 nd trimester group, n=24	3 rd trimester group, n=24	ANOVA*
				p-value
Fz1	97.34±5.33	100.60±6.79	99.86±5.69	0.147
Fz2	100.58±6.81	104.10±6.61	103.49±5.14	0.125
Fz min	77.49±7.69	85.19±7.35	85.16±6.75	0.008*
Fz1-min	18.76±5.08	14.79±7.48	14.86±5.51	0.042
Fz2-min	23.83±7.20	19.45±8.35	18.49±5.68	0.028
FyB	12.41±2.48	12.18±2.39	12.04±2.27	0.867
FyP	16.61±2.54	16.85±2.61	16.85±2.24	0.929
FxL	4.07±2.15	4.06±1.67	4.02±1.24	0.994
FxM	4.57±2.66	4.81±1.87	4.65±1.63	0.920

Note. Data are presented as mean ± standard deviation, *Significance level from ANOVA between the three groups ($p<0.05$), Fz1: vertical GRF first peak, Fz2: vertical GRF second peak, FyB: braking force, FyP: propulsion force, FxL: lateral GRF, FxM: medial GRF.

Table 3. The time variables (in seconds) and walking velocity (meter/second) of the non-pregnant, 2nd trimester and 3rd trimester pregnant groups

Time variables	Non-pregnant group, n=24	2 nd trimester group, n=24	3 rd trimester group, n=24	ANOVA*
				p-value
Fz1 time	0.16±0.02	0.18±0.03	0.18±0.03	0.024*
Fz2 time	0.49±0.03	0.52±0.05	0.52±0.03	0.005*
Fz min time	0.31±0.03	0.34±0.05	0.34±0.04	0.001*
FyB time	0.10±0.02	0.12±0.02	0.12±0.02	0.010*
FyP time	0.56±0.03	0.60±0.04	0.60±0.03	0.001*
FxL time	0.10±0.05	0.13±0.04	0.14±0.05	0.010*
FxM time	0.51±0.06	0.56±0.07	0.55±0.07	0.011*
Walking velocity	1.04±0.11	1.04±0.12	0.98±0.10	0.465

Note. Data are presented as mean ± standard deviation, *Significance level from ANOVA between the three groups, Fz1: vertical GRF first peak, Fz2: vertical GRF second peak, FyB: braking force, FyP: propulsion force, FxL: lateral GRF, FxM: medial GRF.

the previous studies that did not report any changes in the vertical or anterior components of GRF (Abu Osman, & Mat Ghazali, 2002; McCrory, et al., 2011). However, there was an increase in Fz min. These results suggest that the downward acceleration for the advancement of the body of the pregnant women and respective force production in the transmission of weight are smaller in the late pregnancy (Perry, 1992). Furthermore, there was no significant difference in the body weight of the three groups that enable us to exclude the effect of increased body weight during pregnancy on GRFs.

These findings indicate that the configuration of the vertical GRF is significantly flatter. The flatter pattern results from a decreased mid-stance valley of GRF, which is reflected by a higher Fz min. The vertical GRF reflects the rise and fall of COG; the increase in Fz min, the decrease in Fz1-Fz min and Fz2-Fz min indicate that the pregnant women have less vertical movement of their COG at mid-stance than the non-pregnant women. The reduced vertical fluctuation of GRF indicates that the pregnant women adopt a walking pattern that diminishes the downward body motion due to the increased trunk mass during pregnancy. It may be a strategy used by the pregnant women to decrease COG movement and, hence, decrease energy expenditure and make their gait smooth and efficient (Simoneau, 2002).

The 2nd peak of the vertical GRF reflects the combined push-off provided by the plantar flexors and the need to reverse the downward movement of the body that occurs in the terminal stance through a pre-swing (Simoneau, 2002). This indicates that the pregnant women maintain their ability to push-off despite the increased abdominal mass. However, it is unknown if the pregnant women possibly increase the propulsive muscle activities (plantar flexors) to maintain the ability to push-off or not because muscles activities have not been investigated in this study. A previous work has reported an increased demand on the plantar-flexor muscles as reflected by the increased plantar-flexors moment in the 3rd trimester compared with one year postpartum (Foti, et al., 2000). However, a recent work reported a significant decrease in the ankle plantar-flexors moment from the 1st to the 3rd trimester of pregnancy (Branco, Santos-Rocha, Vieira, Aguiar, & Aguiar, 2015).

Besides, Branco et al. (2015) conducted a longitudinal study with eleven pregnant women to study changes in GRF. They detected a decrease in the 1st peak and the 2nd peak of the vertical GRF as well as an increase in the minimum of the vertical GRF of the right leg in the third trimester compared with six months postpartum. Their findings in the 1st and 2nd peaks of the vertical GRF differ from those of the present study. The discrepancy may be related to the difference in the design between the studies. However, the decreased 1st and 2nd peaks as

well as the increased minimum peak of the vertical GRF, found by Branco et al., (2015), confirms the suggestion that the pregnant women assume a flatter pattern of the vertical GRF, which is detected in the present study.

It is known that walking velocity affects the magnitude of the GRF peaks (Andriacchi, Ogle, & Galante, 1977; Hsiang & Chang, 2002). It was supported by the current findings, which revealed that there was no significant difference in walking velocity and the magnitude of the first and second peaks of GRFs of the three groups. So, maintaining the first and the second peak of GRF unchanged and increasing the minimum peak may be a physiological mechanism to keep loading unchanged and with a decreasing upward movement of the pregnant women at midstance (Simoneau, 2002), thus protecting the fetus from shaking.

In the antero-posterior direction, the pregnant women demonstrated no difference in the braking and propulsive forces despite the increased abdominal mass anterior. During walking at a constant velocity, the propulsive force occurring in the late phase of stance balances the braking force occurring in the early stance. That provides balance to the body during the transfer of weight from one lower extremity to the other at the time of a double limb support (Simoneau, 2002). The unchanged braking and propulsive force in the pregnant women compared with their controls means that the pregnant women maintain a state of balance/equilibrium during walking. Moreover, this reflects that the shear forces created between the foot and the ground, required to prevent the foot from slipping forward at the heel contact, remain unchanged. In addition, the unchanged propulsive force and the 2nd peak of the vertical GRF indicate that the forward progression of the body during pregnancy is not affected (Simoneau, 2002).

Although GRF peaks were almost similar in the pregnant women and their controls, the times taken to reach these peaks were prolonged in the pregnant women. In the vertical direction, increased time to reach Fz min and Fz2 peaks indicates that the time from the loading response to the mid-stance and from the mid-stance to the terminal stance have been increased. Also, there was increased time to reach peaks of braking force, propulsion force and peaks of the medio-lateral GRF. The increased time to reach GRF peaks may be a strategy to maximize stability during pregnancy. Previous findings suggested increased stance phase time and foot contact time in the pregnant women. This suggestion is confirmed by numerous studies, which have reported longer stance time in the last trimester (Forczek & Staszkiwicz, 2012; Gimunová, et al., 2015; Karadag-Saygi, et al., 2010). Significant increases in contact times under the forefoot and longer floor contact times were found during pregnancy

(Goldberg, Besser, & Selby-Silverstein, 2001; Karadag-Saygi, et al., 2010). Moreover, the peak pressures were higher in the mid-foot of both feet and on the lateral side of the right forefoot in the pregnant women (Nyska, et al., 2001).

Few studies have investigated GRFs during pregnancy; McCrory et al. (2011) reported no differences in the vertical GRFs between trimesters when controlling walking velocity. In addition, Santos, Gil, Marques, Boas, and da Silva (2008) found no changes in vertical and antero-posterior peaks of GRF of the right limb and prolonged time to reach the 1st peak of the vertical GRF and propulsion peak of the antero-posterior GRF in ten pregnant women, which are in agreement with the findings of this study. They evaluated GRF using treadmill walking, which differs from overground walking and make limited interpretation of GRF results. In addition, they mentioned that a small number of the participants and the variation in the anthropometric parameters between participants were the major limitations to their study.

There was no significant difference between the three groups regarding the medio-lateral force that concurs with the findings of Lymbery and Gilleard (2005) who reported that the medio-lateral component of GRFs showed no significant changes but tended to be higher in late pregnancy. However, it was found that in late pregnancy women had a more medial reaction for the left lower limb, particularly during the loading response phase (Branco, Santos-Rocha, Aguiar, Vieira, & Veloso, 2013; Takeda, Junji, Aya, Sigeko, & Yois, 2009). Recently, Krkeljas (2018) investigated the changes in gait and posture control as factors of stability during walking at different stages of pregnancy. His results showed that the gait kinematics did not differ between the pregnancy trimesters; however, there were significant lateral trunk lean, and medio-lateral deviations in COG and COP. Furthermore, Vico Pardo, López Del Amo, Pardo Rios, Gijon-Nogueron, and Yuste (2018) reported that during pregnancy there was increased foot pronation, which progressed through the three trimesters of pregnancy. However, these changes were not enough to cause a change in the medio-lateral GRF.

Limitations and future research studies

This study has some limitations. Firstly, the GRF of the left leg was not assessed to compare if there was asymmetry in the GRF of both legs in the pregnant women. Hence, some of previous studies

(Branco, et al., 2015; Lymbery & Gilleard, 2005; McCrory, et al., 2011; Takeda, et al., 2009). Branco, Santos-Rocha, Aguiar, Vieira, and Veloso (2016) reported that a greater instability in the frontal plane of the pregnant women and the compensations derived from imbalances could happen only in one of the limbs to maintain balance. So, more research is required to compare and analyze the two sides of the body. Secondly, the temporal parameters of gait, including the double limb support time and the single limb support time that can explain the increased time parameters of GRF, were not investigated in this study. Thirdly, the participants were tested during their self-selected speed that was utilized by most of the recent studies (Aguiar, et al., 2015; Branco, et al., 2015; Krkeljas, 2018; McCrory, et al., 2011), that may affect the values of GRFs. Hessert et al. (2005) stated that GRFs were affected by walking speed and recommended to examine the GRFs during a constant speed. As a result of this contradiction, more study is required to compare the effects of ground and treadmill walking on GRFs. Fourthly, the current study investigated only components of GRFs without consideration of other kinetic parameters as joints moment, especially those of the lower extremities and kinematic parameters such as joint angles. So, it is recommended to explore the relationship between GRFs and joints moments and angular kinematics. More studies are warranted to investigate the relationship between changes in GRF during walking and specific foot pressure distribution in the pregnant women during different trimesters. Finally, further study using electromyography is needed to assess if there is a change in the activities of plantar-flexor muscles during different trimesters of pregnancy and its relation with the 2nd peak of the vertical GRF.

In conclusion, the pregnant women experienced increases in the minimum peak of the vertical GRF and decreases in the difference between $Fz1$ and Fz_{min} and the difference between $Fz2$ and Fz_{min} . Moreover, the results showed increases in the time taken to reach the peaks of the vertical, antero-posterior and medio-lateral GRF. These changes revealed that the pregnant women assumed a flatter pattern of the vertical GRF and decreased the vertical excursion of COG during walking to make their gait efficient and smooth. Furthermore, the increased time to reach the peaks of GRF may be a strategy used by the pregnant women to maximize their balance during walking.

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