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# Ground reaction forces during stair locomotion in pregnancy

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ABSTRACT

Pregnant women experience numerous physical alterations during pregnancy which may place them at an increased risk of falls. The purpose of this study was to examine ground reaction forces (GRFs) during staircase locomotion in pregnant and non-pregnant women.

*Methods:* Data were collected on 29 pregnant women in their second and third trimesters, and on 40 control women. Subjects walked at their freely chosen speeds during stair ascent and descent. A force plate imbedded in the second stair, but structurally independent of the staircase, was used to collect GRF data (1080 Hz). A marker placed on the L3/L4 spinal segment was used to determine ascent and descent velocity from a motion-capture system. In the statistical analyses, trimester (control, second trimester, third trimester) and subject were the independent variables. Stance time and ascent/descent velocity were analyzed with an ANOVA. Mediolateral excursion of the COP during the step was analyzed with an ANCOVA. The GRFs were categorized into anterioposterior, mediolateral, and vertical forces. A two factor MANCOVA (subject, trimester) was performed on each GRF category. Mass and velocity served as covariates in each analysis ($\alpha = 0.05$).

*Results:* The mediolateral excursion of the COP during ascent was greater in the third trimester ($p = 0.04$). The anterioposterior braking impulse was greater in both ascent ($p = 0.01$) and descent ($p = 0.01$) during pregnancy. The vertical GRF loading rate during descent was greater in pregnant women than in controls ($p = 0.04$).

*Conclusion:* These alterations are likely related to increased instability during stairway walking and could contribute to increased fall risk during pregnancy.



## 1. Introduction

Numerous anatomical, physiological, and hormonal alterations occur during pregnancy [1–6] and are related to modifications to gait [7], sit-to-stand biomechanics [8–10], and changes in mechanical loading and joint kinetics [4,11]. Although few alterations in joint kinematics have been reported for level-walking [7], increased lower extremity joint moments and powers are seen [7], as well as greater step width and increased mediolateral trunk movement in pregnancy [7,11]. Lymbery and Gilleard found no differences in ground reaction forces (GRFs), walking speed, or stance time during late pregnancy compared to two months post-partum [11]. Examination of GRFs from level walking did not reveal any differences between trimesters, however, velocity slowed with advancing pregnancy, making it a significant covariate for many of the GRF variables [12]. Additionally, the average woman gains approximately 15 kg during pregnancy [3,11]. Because GRFs are highly correlated to body mass [13], mass must be considered in the analysis.

Staircase locomotion is reported to be one of the most challenging activities of daily living by community dwelling adults [14]. Bertucco and Cesari reported a greater impact peak and smaller anterioposterior push-off peak in young individuals when compared to older adults [15]. However, despite the fact that 40% of the falls experienced by pregnant women occur on stairs [16], little research has been performed on staircase locomotion during pregnancy.

The purpose of this study was to compare GRFs during stair ascent and descent in the second and third trimesters of pregnant women with those of non-pregnant women. We hypothesized that the mediolateral GRF impulses would be larger in pregnant

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women, particularly during their third trimester, because of the larger side to side movement typically demonstrated by pregnant women. For this reason, we also hypothesized that mediolateral COP excursion during stance would be greater in the pregnant women. Because others have reported that significant correlation between body mass [13] and velocity [12] and GRFs, mass and velocity were considered as covariates in the analysis.

## 2. Methods

### 2.1. Subjects

Forty-one pregnant and 40 non-pregnant women between 18 and 45 years participated in this study. Subject demographics are shown in Table 1. Control and pregnant participants were matched to within 2 $kg/m^2$ body mass index, based on the pregnant subjects' self-reported pre-pregnancy mass. Mass was significantly different between the control group and each of the trimesters of the pregnant group ($p < 0.001$).

Data of the non-pregnant control subjects were collected in the week following menses when the concentrations of estrogen and progesterone are low. These hormones influence movement patterns, flexibility, and dexterity [17–19]; therefore, we wanted to standardize when the control women were tested. Pregnant subjects participated in two data collection sessions, the first of which occurred in their second trimester (20.9 ± 1.2 weeks of gestation). The second session occurred during their third trimester at 35.8 ± 1.5 weeks.

Pregnant participants were recruited through the UPMC Womancare Research Registry in the beginning of their second trimester. Non-pregnant controls were recruited via word of mouth and advertisements. Exclusion criteria for either group included: not between 18 and 45 years, lower extremity fracture within five years, lower extremity sprain within one year, current back or knee pain, history of diabetes or any condition which could affect sensation, history of ligament rupture at the ankle or knee, being a current smoker, taking any medication which could affect gait or balance mechanics, or typically consuming more than one alcoholic drink per day. Additional exclusion criteria for the pregnant group included gestation beyond the 20th week of pregnancy, current multiple gestation, or a history of any of the following: delivery of an older child prior to 36 weeks of gestation, toxemia, gestational hypertension, pre-eclampsia, or gestational diabetes. Potential subjects were also excluded if they were considered to have a high risk pregnancy.

Twelve pregnant subjects did not participate in their third trimester testing session. The reasons were as follows: premature delivery of the baby ($n = 4$), decision to withdraw from study ($n = 4$), pregnancy-related complications ($n = 2$), injuries sustained from a fall required bed rest ($n = 1$), and relocation out of the area ($n = 1$). Data from these women are not included in the study.

### 2.2. Procedures

Subjects reported to the Human Movement and Balance Laboratory on the campus of the University of Pittsburgh for testing. Following an explanation of experimental procedures, written informed consent was obtained. Height and mass were obtained using a standard medical scale and stadiometer. Subjects wore comfortable clothing and athletic shoes. A spherical retroreflective marker was placed on the L3/L4 spinal segment.

Subjects practiced walking up and down a wooden four-step staircase. The rise, run, and width of each stair was 20.3 cm, 26.8 cm, and 91.4 cm, respectively. A 91.4 cm by 69.9 cm platform at the top of the staircase provided room to turn around after ascent. A handrail, on the subject's left side during ascent and right side during descent, was provided. The platform at the top was surrounded by a rail to prevent a fall from the platform. Subjects were told to lightly touch the handrail only if needed. No force measurements were made on the handrail.

Each subject wore a shoulder and hip harness for protection in case of a fall. No straps were placed around the abdomen. A laboratory assistant operated a belay system that would have caught in the subject in the event of a fall. However, no subject fell during the testing session. A Bertec force plate (Model 4060A, Bertec Corp, Columbus, OH, 1080 Hz) was used to collect GRF data. The force plate, located in the second stair, was structurally isolated from the staircase in order to prevent vibrations from the subject walking on the staircase from confounding the force data. In order to reduce the incidence of targeting the force plate, subjects were not told about the force plate.

Movement of the marker on the L3/L4 spinal segment was captured with a VICON system (VICON, Inc., Denver, CO, 120 Hz). Horizontal and vertical displacements of the L3L4 marker were calculated from foot-strike on the first stair to toe-off of the last stair of the trial. The time between first step foot-strike to last step toe-off was also determined. Total displacement was then calculated using the Pythagorean theorem. From this, ascent and descent velocities were calculated as the average velocity of the marker during the trial. Subjects walked at their freely chosen speeds. Five trials were collected of the right leg during ascent and the left leg during descent. Rest periods were provided as needed.

The GRF data were processed in Matlab (Version R2008a. Mathworks, Inc., Natick, MA). Data were filtered with a fourth order low-pass, phaseless Butterworth filter with a cutoff frequency of 50 Hz. Heel contact was determined when the vertical GRF exceeded 5% of body weight. Toe-off occurred when the vertical GRF went below 5% of body weight. Mediolateral excursion of the COP during the stance phase was calculated as the difference between the maximum medial and lateral positions of the COP.

The following variables were determined from the anterioposterior shear forces: braking peak, time to braking peak, propulsive peak, time to propulsive peak, and braking and propulsive impulses. Medial and lateral impulses were determined from the medial-lateral shear forces. Passive peak, time to passive peak, active peak, time to active peak, minimum between peaks, time to minimum between peaks, loading rate, and impulse were calculated from the vertical GRFs. Loading rate was calculated as the passive peak divided by the time to the passive peak. GRF variables are illustrated in Fig. 1.

### 2.3. Statistical analysis

Subjects' age, height and mass were compared with an ANOVA ($\alpha = 0.05$), with the independent variable trimester having three levels (control, second trimester, and third trimester). For both ascent and descent, stance time and walking velocity were analyzed with an ANOVA ($\alpha = 0.05$). Tukey post hoc tests were performed if differences were found between trimesters ($\alpha = 0.05$).

An analysis of covariance (ANCOVA) was performed on the mediolateral excursion of the COP ($\alpha = 0.05$). Trimester and subject were the independent variables and the covariates were mass and velocity. Ascent and descent data were analyzed separately. Tukey post hoc tests were performed when appropriate ($\alpha = 0.05$).

GRF variables were categorized into anterioposterior, mediolateral, and vertical forces, according to the dependent variables specified in the methods section. A multivariate analysis of covariance (MANCOVA) was performed on each category of GRF variables ($\alpha = 0.05$). Again, the independent variables were trimester and subject. Mass and walking velocity were covariates in the model. The ascent and descent force data were analyzed separately and not compared statistically. For each of the above comparisons, Tukey post hoc tests were performed when appropriate ($\alpha = 0.05$).

## 3. Results

### 3.1. Ascent

Ascent velocity was not different between trimesters ($p = 0.31$). Controls ascended at 0.68 ± 0.11 m/s, while pregnant women ascended at 0.61 ± 0.09 m/s in their second trimesters and 0.59 ± 0.07 m/s in their third trimesters. Stance time during ascent also was not different between trimesters ($p = 0.06$). Stance times for the controls, pregnant women in their second trimester, and pregnant women in their third trimesters were 0.67 ± 0.11 s, 0.75 ± 0.11 s, and 0.78 ± 0.11 s, respectively.

The mediolateral excursion of the COP during ascent was significantly greater ($p = 0.04$) during the third trimester (54.4 ± 20.3 mm) compared to the second trimester (47.6 ± 19.4 mm) and to the control group (45.7 ± 20.6 mm). There was no difference between the second trimester and control group. Mass and ascent velocity were both significant covariates in this analysis ($p = 0.04$ and 0.01, respectively).

In the shear forces during ascent, braking impulse was lower ($p = 0.01$) in the control group compared to pregnant women in either trimester (Table 2). No differences were noted between trimesters. No other shear force variables were significantly different between trimesters during ascent. Ascent velocity was

**Table 1**
Subject demographics (mean ± standard deviation).

| | Control group ($n = 40$) | | Pregnant group ($n = 29$) |
|---|---|---|---|
| Age (years) | 26.5 ± 6.4 | | 29.5 ± 4.9 |
| Height (cm) | 165.8 ± 5.6 | | 166.1 ± 6.6 |
| | Control group ($n = 40$) | Second trimester | Third trimester |
| Weeks pregnant | | 20.9 ± 1.2 | 35.8 ± 1.5 |
| Mass (kg)* | 64.7 ± 8.8 | 73.9 ± 9.9 | 81.3 ± 11.1 |

* Subject mass was significantly different between the control group and each of the trimesters ($p < 0.001$). Age and height were also not significantly different between groups ($p > 0.05$).

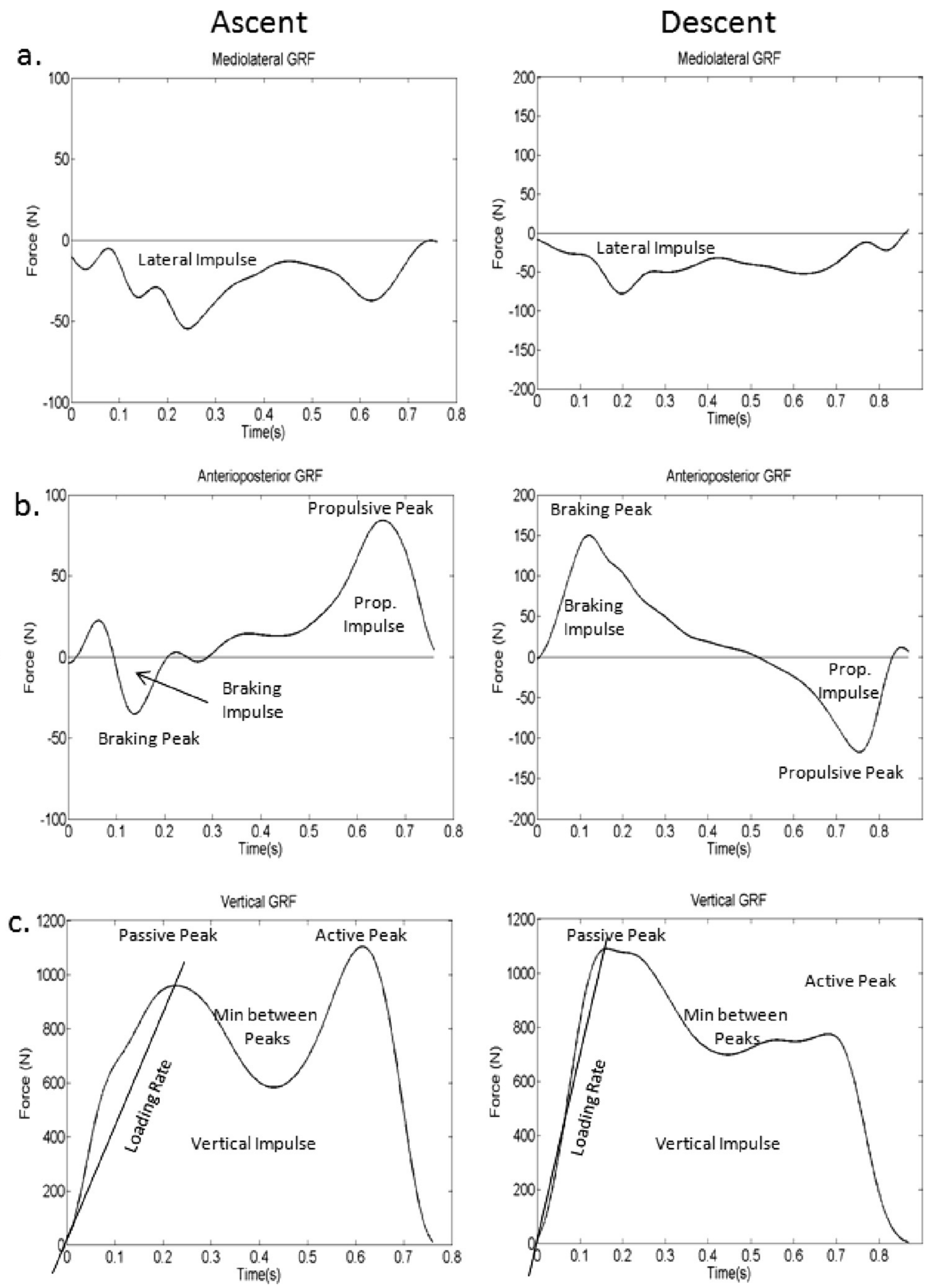


**Fig. 1.** Representative sample of ground reaction forces during ascent (left) and descent (right): (a) mediolateral forces, (b) anterioposterior forces, and (c) vertical forces. The data shown are from a single pregnant subject in her third trimester. Key peaks and impulses are labeled.

a significant covariate ($p < 0.05$) for the braking peak, time to propulsive peak, propulsive impulse, medial impulse and lateral impulse. Mass was a significant covariate for braking peak, propulsive peak, braking impulse, propulsive impulse, medial impulse and lateral impulse.

Vertical force variables were not significantly different between trimesters (Table 3). Ascent velocity was a significant covariate ($p < 0.05$) for all of the vertical GRF variables with the exception of the active peak. Mass was a significant covariate for every vertical GRF variable ($p < 0.05$).

### 3.2. Descent

Descent velocity was not different between trimesters ($p = 0.13$). Descent velocity was $-0.74 \pm 0.12$ m/s for the control group, $-0.66 \pm 0.18$ m/s for the pregnant women in their second trimester and $-0.63 \pm 0.11$ m/s in their third trimester. Stance time during descent was different between controls and each of the trimesters ($p < 0.01$). Controls had a stance time of $0.62 \pm 0.10$ s, while women in their second and third trimesters displayed stance times of $0.66 \pm 0.08$ s and $0.69 \pm 0.10$ s, respectively.

The mediolateral excursion of the COP during descent was not different between the trimesters ($p = 0.07$). Mediolateral excursion of the COP was $66.5 \pm 33.3$ mm in the control group, $55.3 \pm 42.5$ mm in the second trimester, and $60.9 \pm 36.8$ mm during the third trimester. Mass was a significant covariate in the analysis ($p = 0.001$); however, velocity was not ($p = 0.41$).

During descent, the braking peak ($p = 0.05$) was significantly greater in the third trimester than in the second trimester, and it was greater in the second trimester than in the controls. The

**Table 2**
Shear force variables during stair ascent and descent. The data shown are the means (standard deviations). $\alpha = 0.05$. $P_T$ is the $p$-value for the independent factor of "trimester". $P_s$ is the $p$-value for the independent factor of "subject". $P_v$ is the $p$-value for the covariate velocity. $P_m$ is the $p$-value for the covariate mass. Boldface font highlights statistical significance of $p < 0.05$.

| | Ascent | | | | Descent | | | |
|---|---|---|---|---|---|---|---|---|
| | Control | 2nd trim. | 3rd trim. | $p$-value | Control | 2nd trim. | 3rd trim. | $p$-value |
| Braking Pk (N) | −40.7 (27.7) | −54.3 (24.1) | −51.3 (23.0) | $P_T = 0.66$<br>**$P_s = 0.01$**<br>**$P_v = 0.05$**<br>**$P_m < 0.01$** | 101.5 (30.3) | 126.5 (32.3) | 140.6 (33.7) | **$P_T = 0.01$**<br>**$P_s = 0.01$**<br>$P_V = 0.14$<br>**$P_m < 0.01$** |
| Time to braking Pk (s) | 0.131 (0.135) | 0.128 (0.137) | 0.153 (0.156) | $P_T = 0.38$<br>**$P_s = 0.01$**<br>$P_v = 0.71$<br>$P_m = 0.63$ | 0.156 (0.099) | 0.129 (0.026) | 0.131 (0.031) | $P_T = 0.32$<br>**$P_s = 0.01$**<br>**$P_V = 0.03$**<br>$P_m = 0.99$ |
| Propulsive Pk (N) | 64.8 (18.5) | 68.3 (20.7) | 72.2 (19.5) | $P_T = 0.66$<br>**$P_s = 0.01$**<br>$P_v = 0.10$<br>**$P_m < 0.01$** | −70.9 (44.3) | −90.7 (34.0) | −94.1 (34.2) | $P_T = 0.32$<br>**$P_s = 0.01$**<br>$P_V = 0.14$<br>**$P_m < 0.01$** |
| Time to propulsive Pk (s) | 0.435 (0.240) | 0.504 (0.272) | 0.574 (0.245) | $P_T = 0.08$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>$P_m = 0.63$ | 0.478 (0.197) | 0.555 (0.136) | 0.577 (0.164) | $P_T = 0.62$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>$P_m = 0.06$ |
| Braking impulse (Ns) | −3.6 (2.7) | −5.4 (2.7) | −4.8 (2.9) | **$P_T = 0.01$**<br>**$P_s = 0.01$**<br>$P_v = 0.09$<br>**$P_m < 0.01$** | 17.4 (8.3) | 19.1 (6.9) | 23.5 (9.1) | **$P_T = 0.01$**<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** |
| Propulsive impulse (Ns) | 15.3 (7.3) | 17.6 (7.7) | 21.2 (10.8) | $P_T = 0.06$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>**$P_m = 0.01$** | −8.4 (5.1) | −11.9 (4.4) | −12.4 (4.7) | $P_T = 0.18$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>$P_m = 0.33$ |
| Lateral impulse (Ns) | −14.6 (8.3) | −23.9 (12.6) | −28.1 (12.6) | $P_T = 0.32$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** | −20.8 (8.8) | −26.9 (9.5) | −31.1 (12.6) | $P_T = 0.14$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** |
| Medial impulse (Ns) | 2.9 (4.5) | 2.3 (4.5) | 1.7 (4.5) | $P_T = 0.11$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** | 3.2 (6.1) | 1.4 (3.4) | 1.6 (5.0) | $P_T = 0.95$<br>**$P_s = 0.01$**<br>$P_V = 0.58$<br>$P_m = 0.33$ |

braking impulse ($p = 0.01$) was greater in the third trimester than in the second trimester and in the controls, and it was not different between the controls and the second trimester (Table 2). No other shear force variables were significantly different between trimesters. Descent velocity was a significant covariate ($p < 0.05$) for the variables of time to breaking peak, time to propulsive peak, braking impulse, propulsive impulse, and lateral impulse. Mass was a significant covariate ($p < 0.05$) for braking peak, propulsive peak, braking impulse, and lateral impulse.

In the vertical GRFs during descent, time to passive peak, loading rate, active peak, and vertical impulse were significantly different between trimesters (Table 3). Specifically, time to passive peak was different between the third trimester when compared to the second trimester and controls, but it was not different between the second trimester and controls ($p = 0.03$). Loading rate was significantly greater ($p = 0.04$) during pregnancy compared to the non-pregnant controls, but it was not different between trimesters. The active peak during descent and the vertical impulse were greater ($p \leq 0.05$) in the third trimester than in the second trimester, and the second trimester was greater than the controls. Mass was a significant covariate ($p < 0.05$) for the passive peak, time to passive peak, loading rate, minimum between peaks, time to minimum between peaks, active peak, and impulse. Descent velocity was a significant covariate ($p < 0.05$) for the passive peak, time to the minimum between peaks, time to the active peak, and impulse.

## 4. Discussion

The purpose of our study was to examine the effects of advancing pregnancy on GRFs during stair locomotion. We hypothesized that the medial and lateral GRF impulses and the mediolateral excursion of the COP would be larger during pregnancy. Because previous research on GRFs during level walking in pregnancy did not find a pregnancy effect [12], we did not hypothesize that other GRF variables would be affected.

As hypothesized, the mediolateral excursion of the COP during ascent was greater during the third trimester compared to the second trimester and the control group. Ascent velocity and mass were significant covariates in the analysis such that ascending slower and having a greater mass were associated with increased mediolateral COP movement. Alvarez et al. reported that average foot width during pregnancy increases from 89.3 mm to 90.0 mm between the second and third trimesters [20]. Given that COP excursion in our study increased from 47.6 mm to 54.4 mm during this time period, it should be noted that COP excursion occurs over a considerably greater amount of the foot width during the third trimester. Thus, the margin of stability [21], or the distance from the COP to the edge of the base of support, may be less in the third trimester. This may have implications on dynamic stability, particularly during single-limb stance [22].

Others have reported an increased stance width and increased side-to-side motion of the torso during advanced pregnancy [7,11]. In various populations at risk for falls (e.g. elderly individuals and

**Table 3**
Vertical force variables during stair ascent and descent. The data shown are the means (standard deviations). $\alpha = 0.05$. $P_T$ is the $p$-value for the independent factor of "trimester". $P_s$ is the $p$-value for the independent factor of "subject". $P_v$ is the $p$-value for the covariate velocity. $P_m$ is the $p$-value for the covariate mass. Boldface font highlights statistical significance of $p < 0.05$.

| | Ascent | | | | Descent | | | |
|---|---|---|---|---|---|---|---|---|
| | Control | 2nd trim. | 3rd trim. | *p*-value | Control | 2nd trim. | 3rd trim. | *p*-value |
| Passive peak (N) | 717.8 (112.7) | 752.6 (133.5) | 798.1 (106.8) | $P_T = 0.91$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>**$P_m < 0.01$** | 935.5 (156.4) | 1035.6 (208.8) | 1082.1 (155.9) | $P_T = 0.08$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** |
| Time to passive peak (s) | 0.20 (0.04) | 0.25 (0.05) | 0.26 (0.05) | $P_T = 0.89$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>**$P_m < 0.01$** | 0.12 (0.02) | 0.13 (0.02) | 0.13 (0.03) | **$P_T = 0.03$**<br>**$P_s = 0.01$**<br>$P_V = 0.78$<br>**$P_m < 0.01$** |
| Loading Rate (N/s) | 3624.7 (839.7) | 3152.5 (716.8) | 3192.2 (684.2) | $P_T = 0.96$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>**$P_m < 0.01$** | 8110.4 (2212.5) | 8617.6 (2482.1) | 8395.6 (2035.5) | **$P_T = 0.05$**<br>**$P_s = 0.01$**<br>$P_V = 0.30$<br>**$P_m < 0.01$** |
| Minimum between peaks (N) | 464.1 (163.2) | 508.9 (117.6) | 566.5 (110.0) | $P_T = 0.82$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>**$P_m < 0.01$** | 435.3 (122.0) | 513.0 (105.8) | 553.5 (122.3) | $P_T = 0.86$<br>**$P_s = 0.01$**<br>$P_V = 0.92$<br>**$P_m < 0.01$** |
| Time to Min between peaks (s) | 0.38 (0.07) | 0.43 (0.07) | 0.45 (0.08) | $P_T = 0.86$<br>**$P_s = 0.01$**<br>**$P_v < 0.01$**<br>**$P_m < 0.01$** | 0.32 (0.05) | 0.34 (0.05) | 0.35 (0.05) | $P_T = 0.93$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** |
| Active peak (N) | 773.5 (121.2) | 838.5 (135.5) | 908.1 (149.4) | $P_T = 0.93$<br>**$P_s = 0.01$**<br>$P_V = 0.11$<br>**$P_m < 0.01$** | 580.1 (89.0) | 635.0 (106.1) | 689.8 (109.2) | **$P_T = 0.03$**<br>**$P_s = 0.01$**<br>$P_V = 0.98$<br>$P_m = 0.18$ |
| Time to active peak (s) | 0.54 (0.12) | 0.61 (0.10) | 0.63 (0.11) | $P_T = 0.56$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** | 0.45 (0.09) | 0.48 (0.08) | 0.50 (0.09) | $P_T = 0.25$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>$P_m = 0.18$ |
| Impulse (Ns) | 349.8 (77.3) | 433.7 | 479.2 (112.5) | $P_T = 0.41$<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** | 314.3 (69.4) | 376.2 (75.1) | 423.6 (100.9) | **$P_T = 0.01$**<br>**$P_s = 0.01$**<br>**$P_V < 0.01$**<br>**$P_m < 0.01$** |

amputees), mediolateral movement of the COP is increased [23,24]. It is not known if the mechanism for the increased movement of the COP is due to an inherent decrease in stability, or if it is reflective of an increased stance width in an attempt to increase stability in populations prone to falls. Regardless of whether the mediolateral movement of the COP is directly related to a decrease in stability or if it reflects the subject's fall prevention strategy, this variable may be a predictor of an increased fall risk. It is important to note, however, in our study the mediolateral excursion of the COP during descent was not affected by pregnancy.

We also hypothesized that medial and lateral impulse would be larger in the pregnant women. Our results do not support this hypothesis as neither medial nor lateral impulse during ascent or descent were affected by trimester, although walking velocity and subject mass were significant covariates in the analysis. Lymbery and Gilleard reported increased mediolateral forces during gait in pregnancy; however, mediolateral impulses were not calculated in that study [11]. Other studies have reported that slower walking velocities and/or increased mass are related to an increased medial impulse during gait [12,25].

Several anterioposterior shear force variables were affected by pregnancy, even when accounting for body mass and velocity. During descent, the braking peak was greater in the third trimester than during the second trimester, which was also significantly greater than in the control group. In both ascent and descent, the braking impulse was greater in the pregnant women than in the controls. Impulse is calculated as the area under the ground reaction force curve. Thus, a longer support time or a greater magnitude of force would increase the impulse. Because pregnant women demonstrated greater stance times as well as greater braking peaks, their braking impulse was increased.

Previous research on elderly subjects at risk for falls purports that they alter the angle of contact of the lower leg with the ground to reduce the braking force and impulse to lessen the risk of slipping [26]. Similarly, Marigold and Patla stated that after encountering a slippery floor, normal, healthy subjects adapt their gait by reducing the braking impulse and landing more flat-footed [27]. It is unknown if the increased braking impulse seen in pregnant subjects puts them at an increased risk of slipping; however, given that others at risk for falls show a reduced braking impulse as an adaptation to attenuate fall risk, pregnant women may have an increased risk of slipping on stairs. Subsequent research on pregnant women should examine the required coefficient of friction during this task to see if this greater braking impulse would predispose pregnant women to slipping while on the stairs.

During ascent, no vertical GRF variables were different between trimesters, although ascent velocity and subject mass were significant covariates in most of the statistical comparisons. During descent, however, the time to the passive peak was slightly although significantly greater in the pregnant women. Because of the increased body mass that accompanies pregnancy, the loading rates during descent were significantly greater in the pregnant women. Additionally, the active peak, which occurs during propulsion, was greater during pregnancy, particularly in the third trimester. Lymbery and Gilleard reported a greater active peak during gait in late pregnancy [11].

The results of this study are reported without any normalization for body weight. A common practice in gait biomechanics is to normalize GRFs to body weight or mass in order to compare across individuals of various body sizes [11,12,28]. Mullineaux and colleagues reported that normalization of vertical ground reaction forces to mass is appropriate because of the linear relationship between body weight and force [13]. We elected not to do this. Rather, we included subject mass as a covariate in the statistical model. This approach allowed us to examine how the foot-stair contact forces are affected throughout pregnancy, while still accounting for body mass in the statistical analysis. Thus, the transient, temporary nature of pregnancy (which includes weight gain) could be more easily observed.

We did, however, compare our finding with an analysis of mass-normalized variables (i.e. normalized for mass and not including it as a covariate). With the statistical analyses performed in this manner, there were no overall differences in the significant ANOVA results. However, there was a significant post hoc difference in loading rate between the groups ($p < 0.05$). Loading rate was significantly greater in the second and third trimesters than in the controls for the covariate method, whereas when the data were body weight normalized and mass was not a covariate, loading rate was significantly less in the third trimester ($10.7 \pm 2.8$ BW/s) than in the controls ($12.6 \pm 3.5$ BW/s) and the second trimester ($11.8 \pm 3.1$ BW/s). Controls and second trimester subjects showed no differences in body weight normalized loading rate. Our subjects gained an average of 9.2 kg in the second trimester and an additional 7.4 kg in the third trimester, resulting in an average total gain of 16.6 kg. Mullineaux et al. assert that body weight normalization of loading rates does not fully account for subject variance, and that further work is necessary to identify a more appropriate method to normalize loading rates between subjects of different sizes [13]. Thus, we believe our decision to not normalize loading rate to body weight was appropriate.

Quantifying 'stability' in gait and stair locomotion, both dynamic activities, is difficult. Forty percent of pregnant women fall on stairs [16]. The mechanism of these falls is not known; i.e. we do not know if the falls were due to slips, trips, or other events. Data from the current study indicate that a slip may be likely in pregnancy due to the greater braking impulse that would require a greater coefficient of friction on the support surface to prevent the slip. Biomechanists who have studied other populations at risk for falls have attempted to quantify their 'stability' during gait through variables such as COP movement, COP velocity, margin of stability, and COP-COM inclination angle [21,22,29]. The pregnant women in our study demonstrated greater mediolateral movement of the COP than the controls, indicating a possible decrement in dynamic stability. Further research needs to be performed to examine dynamic stability in pregnancy, particularly in pregnant women who have experienced a fall and pregnant women who have not fallen.

## 5. Conclusion

Several GRF variables during staircase locomotion were significantly altered during pregnancy, including the mediolateral excursion of the COP during ascent, the anterioposterior braking impulse in both ascent and descent, and the vertical GRF loading rate during descent. These alterations may contribute to increased fall risk [16] and reflect an altered motor control in pregnancy [6,30].


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## Conflict of interest statement

No author has any financial or personal relationship with other people or organizations that could inappropriately influence their work.

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