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Ground reaction forces during stair locomotion in pregnant fallers and non-fallers ☆

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ABSTRACT

Background: More than 27% of pregnant women fall. Approximately 40% of falls occur during staircase locomotion. The purpose of this study was to examine ground reaction forces in pregnant fallers, pregnant non-fallers, and non-pregnant controls to determine if pregnant fallers display alterations to ground reaction forces that increase their risk of falling on stairs.

Methods: Fifteen pregnant fallers and 14 pregnant non-fallers participated during their second and third trimesters. Forty non-pregnant women served as controls. Subjects ascended and descended a four-step staircase. A force plate in the second stair collected ground reaction forces. Ascent and descent velocities were assessed. In the statistics, group (pregnant faller, pregnant non-faller, control) and subject were independent variables. Stance time and ascent/descent velocity were analyzed with an ANOVA. Mediolateral center of pressure excursion was analyzed with an analysis of covariance. Ground reaction forces were categorized into anterioposterior, mediolateral, and vertical forces and normalized to the subject's bodyweight. A multivariate analysis of covariance was used to compare between groups and subjects for each force category, with velocity as the covariate ($\alpha = 0.05$).

Findings: Pregnant fallers had an increased anterioposterior braking impulse ($P < 0.01$), medial impulse ($P = 0.02$), and minimum between vertical peaks ($P = <0.01$) during ascent. During descent, pregnant fallers demonstrated a smaller anterioposterior propulsive peak and propulsive impulse ($P = 0.03$) and a greater minimum between vertical peaks ($P < 0.01$).

Interpretation: These alterations are likely related to a strategy used by pregnant fallers to increase stability during staircase locomotion.

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1. Introduction

More than 27% of pregnant women fall, making falls a leading cause of trauma-related hospital admissions in pregnancy (Dunning et al., 2010). Forty-percent of falls occur during stair locomotion, although it is unknown if more happen during ascent or descent (Dunning et al., 2010). Many physiological changes associated with pregnancy may be related to this increased fall risk because they may alter the position of the center of mass (CoM) or decrease dynamic control during gait. These alterations include: increased spinal lordosis (Dumas et al., 1995), increased ligamentous laxity (Calguneri et al., 1982), substantial weight gain (Calguneri et al., 1982; McCrory et al., 2010a), decreased abdominal muscle strength (Gilleard and Brown, 1996), swelling of the extremities (Kent et al., 1999), and decreased neuromuscular coordination (Wu et al., 2004).

Biomechanical alterations associated with pregnancy include a greater step width and increased mediolateral motion of the torso and CoM during gait in the third trimester (Foti et al., 2000; Lymbery and Gilleard, 2005). The greater step width may be an adaptation to increase frontal plane stability in reaction to the increased side-to-side trunk displacement. No significant pregnancy-related differences in ground reaction force (GRF) variables during level walking have been reported (Lymbery and Gilleard, 2005), although walking velocity may slow in pregnancy (McCrory et al., 2011), making it a confounding variable when examining the effect of pregnancy on GRF variables.

Staircase locomotion is reported to be one of the most challenging activities of daily living by community dwelling adults (Verghese et al., 2008). In the general population, falls are more likely to occur during descent (Tinetti et al., 1988). Healthy older individuals without a history of falls display a lower vertical passive peak and anterioposterior push-off peak during ascent and an increased vertical loading rate and anterioposterior braking peak during descent when compared to

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younger women (Bertucco and Cesari, 2009; Hamel et al., 2005). Older fallers display slower descent velocities and greater peak braking forces than non-fallers (Vanicek et al., 2010). In a previous study, we examined the effect of advancing pregnancy on GRF variables during staircase locomotion. The mediolateral excursion of the center of pressure (CoP) and the anterioposterior braking impulse during ascent increased during pregnancy, particularly in the third trimester (McCrory et al., 2013). The increased mediolateral excursion of the CoP may be indicative of a decrease in dynamic postural control or it may be a reaction to the increased side-to-side movement of the CoM seen during gait. The increased braking impulse may increase fall risk because a greater frictional force would be required to prevent a slip.

Given that pregnant women undergo a number of physiological changes that may decrease dynamic stability and that other populations at an increased risk of falling display changes to their ground reaction forces during staircase locomotion, it is important to study ground reaction forces in pregnant fallers to better understand the reasons behind the increased fall risk on stairs in pregnancy. We have previously reported that the pregnant fallers who participated in the current study displayed biomechanical differences when compared to pregnant non-fallers in other measures such as CoP movement following perturbations to quiet stance and in trunk mechanics during gait. Specifically, pregnant fallers showed less anterioposterior movement of the CoP (McCrory et al., 2010b) and a stiffer ankle (Ersal et al., 2012) in response to an anterioposterior translational perturbation to quiet stance. Additionally, pregnant fallers exhibited less lateral lean of the trunk at heel strike as well as less thorax rotation throughout the stride (McCrory et al., 2012). These previous findings suggest that GRF variables may also differ between pregnant fallers and non-fallers during stair locomotion.

The purpose of this study was to compare GRF variables during stair locomotion in pregnant women who have fallen while pregnant, pregnant women who have not fallen, and non-pregnant women. Based on our previous research, we hypothesized that the mediolateral CoP excursion and the anterioposterior braking impulse would be greater in the pregnant fallers compared to the pregnant non-fallers and controls.

2. Methods

2.1. Subjects

Forty-one pregnant and 40 non-pregnant women between the ages of 18 and 45 participated (Table 1). Control and pregnant participants were matched to within 2 kg/m^2 BMI, based on the pregnant subject's self-reported pre-pregnancy mass. Mass was significantly different between each of the trimesters and the controls ($P < 0.001$); however, it was not different between pregnant fallers and non-fallers ($P = 0.421$). Age and height were not different between groups ($P > 0.05$). Pregnant subjects participated in two visits, each occurring in the middle of their second and third trimesters. Data of control subjects were collected in a single session in the week following menses when estrogen and progesterone concentrations are low (Tortora and Brabowski, 2000), because estrogen and progesterone may influence movement patterns and dexterity (Lebrun, 1994; Posthuma et al., 1987; Yack et al., 2003).

Table 1
Subject demographics: mean (standard deviation).

	Control group (n = 40)	Pregnant group (n = 29)			
		Non-fallers (n = 14)		Fallers (n = 15)	
Age (yrs)	26.5 (6.4)	30.8 (3.7)		29.4 (4.5)	
Height (cm)	165.8 (5.6)	167.4 (7.2)		165.7 (6.4)	
		Second trimester	Third trimester	Second trimester	Third trimester
Weeks pregnant		20.8 (1.3)	35.8 (1.6)	21.1 (1.2)	35.7 (1.4)
Mass	64.7 (8.8)	73.4 (11.2)	82.1 (12.5)	73.3 (8.9)	81.0 (9.6)

Subject mass was significantly different between the control group and each of the trimesters ($P < 0.001$). Subject mass, age, weeks pregnant, and height were not significantly different between pregnant fallers and pregnant non-fallers ($P > 0.05$).

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 placed around the community. Exclusion criteria for subjects in either group included: lower extremity fracture within the last five years or sprain within the last year, current back or knee pain, history of diabetes or any other condition which could affect sensation, or history of lower extremity ligament rupture. Subjects were also excluded if they were a current smoker, if they currently took any medication which would affect gait or balance, or had an average consumption of more than one alcoholic drink per day. Additional exclusion criteria for pregnant women included gestation beyond the twentieth week, current multiple gestation, history of 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 had a high risk pregnancy.

Twelve pregnant women withdrew from study participation following their first visit for the following reasons: chose not to participate ($n = 4$), pregnancy complications ($n = 2$), subject injured in a fall ($n = 1$), preterm delivery ($n = 4$), and relocation away from the area ($n = 1$). Only data from the 29 pregnant subjects who completed the study are included.

2.2. Procedures

Subjects reported to the Human Movement and Balance Laboratory at the University of Pittsburgh for testing. Experimental procedures were explained to the subject. Following this, written informed consent was obtained.

Pregnant subjects were surveyed about falls during this pregnancy. A fall was defined as a loss of balance such that another part of the body other than a foot touched the ground. Twenty-four falls were reported by 15 of the 29 women in the study (McCrory et al., 2010b). If a subject stated that she fell during this pregnancy, she was categorized as a “pregnant faller”. Those who did not fall were categorized as “pregnant non-fallers” ($n = 14$). Additional results of the falls survey were previously reported (McCrory et al., 2010b).

Height and mass were obtained using a standard medical scale and stadiometer. Subjects wore comfortable clothing and their own athletic shoes. A spherical retroreflective marker was placed on the L3L4 spinal segment for use in determining walking velocity.

Subjects practiced ascending and descending a four-step wooden staircase. The rise, run, and width of each stair were 20.3 cm, 26.8 cm, and 91.4 cm, respectively. A handrail, located on the subject's left side during ascent and right side during descent, was provided. A 91.4 cm by 69.9 cm platform was provided at the top of the staircase to allow subjects to comfortably turn around. Subjects were instructed to lightly touch the handrail only if needed. No force measurements were made on the handrail. Each subject wore a harness for protection in case of a fall. A laboratory assistant operated a belay system to catch the subject should a fall occur. However, no subject fell during testing.

A Bertec force plate (Model 4060A, Bertec Corp, Columbus, OH, USA, 1080 Hz) located in the second stair was used to collect GRF data. The force plate was structurally isolated from the staircase. Movement of the L3L4 marker was captured with a VICON system (VICON, Inc., Denver, CO, USA, 120 Hz); from this, ascent and descent velocities were calculated as the average resultant velocity of the L3L4 marker. Five trials of the right leg during ascent and the left leg during descent were obtained. Rest periods were provided as needed.

GRF data were processed in Matlab (Version R2008a. Mathworks, Inc., Natick, MA, USA). Data were filtered with a fourth order low-pass, phaseless Butterworth filter with a cutoff frequency of 50 Hz. Initial contact was defined as when the vertical GRF exceeded 5% of body weight. Mediolateral excursion of the CoP 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 GRF variables. Loading rate was calculated as the passive peak divided by the time to the passive peak. All GRFs variables were normalized to the subject's body weight. An illustration of the variables is provided in a previous publication (McCrory et al., 2013).

2.3. Statistical analysis

In each statistical comparison, fall group (pregnant faller, pregnant non-faller, and non-pregnant control) and subject were designated as the independent variables. Data from the second and third trimesters were averaged. A comparison between the trimesters can be found in McCrory et al. (2013).

An ANOVA was performed to determine if the fall groups differed by age, height, and mass. For both ascent and descent, stance time and walking velocity were analyzed with an ANOVA ($\alpha = 0.05$). An analysis of covariance (ANCOVA) was then performed on the mediolateral excursion of the CoP ($\alpha = 0.05$). Velocity was the covariate in the analysis. Ascent and descent data were analyzed separately.

GRF variables were categorized into anterioposterior, mediolateral, and vertical forces, as detailed in the methods section. A two-factor (group, subject) MANCOVA (covariate: velocity) was performed on each category of GRF variables ($\alpha = 0.05$). Ascent and descent 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 controls, pregnant fallers, and pregnant non-fallers ($P = 0.09$). Pregnant fallers and pregnant non-fallers both ascended at 0.60 (0.10) m/s, while controls ascended at ascended at 0.68 (0.11) m/s. Stance time was not different between groups ($P = 0.45$). Stance time for the controls was 0.67 (0.11) s, while it was 0.76 (0.10) s for the pregnant women, regardless of fall group. The mediolateral excursion of the CoP during ascent was not different between groups (pregnant fallers: 51.8 (20.8) mm, pregnant non-fallers: 49.1(19.3) mm, controls: 45.7(20.6) mm, $P = 0.70$). Ascent velocity was a significant covariate in this analysis ($P = 0.03$).

In the shear forces during ascent, anterioposterior braking impulse ($P < 0.01$) and the time to the braking peak force ($P < 0.01$) were larger in pregnant fallers than the non-fallers and controls, while no differences were noted between non-fallers and controls (Table 2). The medial impulse ($P < 0.01$) was larger in the pregnant fallers than pregnant non-fallers, which in turn was larger than the controls (Table 2). Ascent velocity was a significant covariate ($P < 0.05$) for the braking peak, propulsive peak, time to propulsive peak, propulsive impulse, and medial impulse.

In the vertical forces, the minimum between the vertical GRF peaks was larger in the pregnant fallers compared to the controls, which was also greater than the pregnant non-fallers ($P < 0.01$) (Table 3). The time to the minimum between peaks were different between groups ($P = 0.05$ and 0.02, respectively), such that their magnitudes were greater in both the pregnant fallers and pregnant non-fallers as compared to the controls, but no difference was noted between pregnant fallers and non-fallers. Velocity was a significant covariate ($P < 0.05$) for all of the vertical GRF variables.

3.2. Descent

Descent velocity was not different between groups ($P = 0.22$). Descent velocity was -0.74 (0.12) m/s for the control group, and

Table 2
Shear force variables during stair ascent and descent. The data shown are the means (standard deviations).

	Ascent				Descent			
	Control	Pregnant non-faller	Pregnant faller	*P*-value	Control	Pregnant non-faller	Pregnant faller	*P*-value
Braking Pk (BW)	−0.064 (.042)	−0.072 (.027)	−0.072 (.037)	$P_F = 0.75$ **$P_s < 0.01$** **$P_v = 0.03$**	0.161 (0.047)	0.178 (0.038)	0.173 (0.036)	$P_F = 0.25$ **$P_s < 0.01$** $P_v = 0.24$
Time to braking Pk (s)	0.13 (0.14)	0.11 (0.05)	0.17 (0.20)	**$P_F < 0.01$** **$P_s < 0.01$** $P_v = 0.71$	0.16 (0.10)	0.13 (0.03)	0.14 (0.03)	$P_F = 0.14$ **$P_s < 0.01$** **$P_v = 0.03$**
Propulsive Pk (BW)	0.100 (0.026)	0.094 (0.020)	0.094 (0.030)	$P_F = 0.95$ **$P_s < 0.01$** **$P_v = 0.03$**	−0.129 (0.056)	−0.130 (0.031)	−0.111 (0.055)	**$P_F < 0.01$** **$P_s < 0.01$** $P_v = 0.27$
Time to propulsive Pk (s)	0.43 (0.24)	0.53 (0.26)	0.53 (0.27)	$P_F = 0.93$ **$P_s < 0.01$** **$P_v < 0.01$**	0.48 (0.20)	0.59 (0.09)	0.54 (0.19)	**$P_F = 0.04$** **$P_s < 0.01$** **$P_v < 0.01$**
Braking impulse (BW s)	−0.005 (0.004)	−0.006 (0.003)	−0.008 (0.004)	**$P_F < 0.01$** **$P_s < 0.01$** $P_v = 0.13$	0.025 (0.010)	0.027 (0.009)	0.028 (0.010)	$P_F = 0.35$ **$P_s < 0.01$** **$P_v = 0.05$**
Propulsive impulse (BW s)	0.026 (0.013)	0.025 (0.008)	0.023 (0.010)	$P_F = 0.07$ **$P_s < 0.01$** **$P_v < 0.01$**	−0.015 (0.007)	−0.017 (0.005)	−0.015 (0.007)	$P_F = 0.03$ **$P_s < 0.01$** $P_v < 0.27$
Medial impulse (BW s)	−0.023 (0.013)	−0.031 (0.015)	−0.036 (0.015)	**$P_F = 0.02$** **$P_s < 0.01$** **$P_v < 0.01$**	−0.035 (0.015)	−0.037 (0.013)	−0.039 (0.014)	$P_F = 0.16$ **$P_s < 0.01$** **$P_v < 0.01$**
Lateral impulse (BW s)	0.005 (0.007)	0.003 (0.006)	0.003 (0.006)	$P_F = 0.82$ **$P_s < 0.01$** $P_v = 0.67$	0.003 (0.007)	0.001 (0.004)	0.002 (0.007)	$P_F = 0.09$ **$P_s < 0.01$** $P_v = 0.75$

P_F is the *P*-value for the independent factor of "fall group". P_s is the *P*-value for the independent factor of "subject". P_v is the *P*-value for the covariate velocity. Variables that were statistically significant are highlighted in bold.

Table 3
Vertical force variables during stair ascent and descent. The data shown are the means (standard deviations).

	Ascent				Descent			
	Control	Pregnant non-faller	Pregnant faller	*P*-value	Control	Pregnant non-faller	Pregnant faller	*P*-value
Passive peak (BW)	1.11 (0.15)	1.04 (0.06)	1.02 (0.12)	$P_F = 0.47$ **P_s < 0.01** **P_v < 0.01**	1.45 (0.20)	1.40 (0.18)	1.40 (0.17)	$P_F = 0.91$ **P_s < 0.01** **P_v < 0.01**
Time to passive Peak (s)	0.20 (0.04)	0.25 (0.04)	0.25 (0.06)	$P_F = 0.12$ **P_s < 0.01** **P_v < 0.01**	0.12 (0.02)	0.13 (0.03)	0.13 (0.03)	$P_F = 0.06$ **P_s < 0.01** $P_v = 0.78$
Loading rate (BW/s)	5.68 (1.52)	4.33 (0.84)	4.21 (1.00)	$P_F = 0.61$ **P_s < 0.01** **P_v < 0.01**	12.89 (3.26)	11.74 (3.03)	11.13 (2.93)	$P_F = 0.08$ **P_s < 0.01** $P_v = 0.11$
Minimum between peaks (BW)	0.72 (0.26)	0.67 (0.10)	0.75 (0.14)	**P_F < 0.01** **P_s < 0.01** **P_v < 0.01**	0.66 (0.16)	0.67 (0.08)	0.73 (0.10)	**P_F < 0.01** **P_s < 0.01** $P_v = 0.11$
Time to min between peaks (s)	0.38 (0.07)	0.44 (0.05)	0.43 (0.10)	**P_F = 0.02** **P_s < 0.01** **P_v < 0.01**	0.32 (0.05)	0.35 (0.04)	0.34 (0.06)	$P_F = 0.96$ **P_s < 0.01** **P_V < 0.01**
Active peak (BW)	1.20 (0.17)	1.15 (0.11)	1.16 (0.12)	$P_F = 0.60$ **P_s < 0.01** **P_v < 0.01**	0.88 (0.09)	0.87 (0.07)	0.85 (0.08)	$P_F = 0.34$ **P_s < 0.01** $P_V = 0.93$
Time to active peak (s)	0.54 (0.12)	0.62 (0.07)	0.61 (0.14)	$P_F = 0.14$ **P_s < 0.01** **P_v < 0.01**	0.45 (0.09)	0.51 (0.06)	0.47 (0.10)	**P_F < 0.01** **P_s < 0.01** **P_v < 0.01**
Impulse (BWs)	0.54 (0.07)	0.60 (0.06)	0.60 (0.11)	$P_F = 0.45$ **P_s < 0.01** **P_V < 0.01**	0.48 (0.07)	0.52 (0.06)	0.50 (0.07)	$P_F = 0.14$ **P_s < 0.01** **P_V < 0.01**

P_F is the *P*-value for the independent factor of "fall group". P_s is the *P*-value for the independent factor of "subject". P_v is the *P*-value for the covariate velocity. Variables that were statistically significant are highlighted in bold.

pregnant fallers and pregnant non-fallers descended at −0.65 (0.13) m/s and −0.64 (0.18) m/s, respectively. Stance time during descent was not different between groups ($P = 0.64$). Controls had a stance time of 0.62 (0.10) s, while pregnant fallers and pregnant non-fallers had descent stance times of 0.67 (0.10) s and 0.67 (0.07) s, respectively. Mediolateral CoP excursion was significantly less in the pregnant women than in the controls: (pregnant fallers: 55.0 (22.0) mm, pregnant non-fallers: 52.6 (26.0) mm, controls: 66.5 (33.3) mm; $P = 0.03$). Descent velocity was not a significant covariate in the analysis ($P = 0.26$).

During descent, the propulsive peak ($P < 0.01$) and time to propulsive peak ($P = 0.04$) were different between groups (Table 2). The propulsive peak was greatest in the pregnant non-fallers and controls, and it was smallest in pregnant fallers. Time to the propulsive peak was longer in pregnant women than in controls, regardless of the subjects being fallers or pregnant non-fallers. The propulsive impulse was significantly larger in the pregnant non-fallers than in the pregnant fallers and controls ($P = 0.03$), while no difference was noted between the latter two groups. Descent velocity was a significant covariate ($P < 0.05$) for time to braking peak, time to propulsive peak, braking impulse, and medial impulse.

In the vertical forces, the minimum between peaks and time to active peak were different between pregnant fallers and pregnant non-fallers (Table 3). The minimum between the peaks was greatest in pregnant fallers, and no difference was noted between the pregnant non-fallers and controls ($P < 0.01$). The time to the active peak was longer in the pregnant non-fallers, while there was no difference between the pregnant fallers and the control women ($P < 0.01$). Descent velocity was a significant covariate ($P < 0.05$) for 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 if women who have fallen while pregnant exhibit altered GRF variables during stair locomotion compared to pregnant non-fallers and non-pregnant women. This information could help discern if pregnant fallers have different mechanics that may place them at a greater risk for falling during staircase locomotion. We previously reported that pregnant fallers have a truncated response of the CoP to a perturbation to quiet stance (McCrory et al., 2010b), a stiffer ankle during the perturbation (Ersal et al., 2012), as well as less movement of the torso during gait (McCrory et al., 2012) compared to pregnant women who did not fall while pregnant. Thus, given that 40% of the falls in pregnancy occur during staircase locomotion (Dunning et al., 2003, 2010), an examination of the biomechanics of staircase locomotion during pregnancy, particularly in regard to pregnant fallers, is warranted.

We hypothesized that the mediolateral excursion of the CoP and the anterioposterior braking impulse would be greater in pregnant fallers during both ascent and descent. Our results only partially support these hypotheses. No differences were found in the mediolateral CoP excursion between groups in ascent, and in descent, the pregnant women demonstrated less mediolateral CoP excursion than did controls. In the anterioposterior forces, the braking impulse was greater in the pregnant fallers during ascent, but not descent.

Contrary to our hypothesis, no differences were found in the mediolateral excursion of the CoP between groups in ascent. During descent, the mediolateral CoP excursion in pregnant subjects was smaller when compared to the controls. This may be a strategy to maintain dynamic stability during pregnancy. Kim (2009) reported that mediolateral CoP excursion is smaller in healthy elderly people compared to young individuals during stair descent, and suggested that the truncated excursion of the CoP may be a control strategy to maintain a more cautious gait in order to increase stability. Interestingly, they also reported that the anterioposterior displacement of the CoP during stair descent is smaller in elderly compared to young individuals (Kim, 2009). That variable was not assessed in our current study. Biomechanists who perform future studies should consider assessing that variable as it may shed insight on fall-risk.

The braking impulse is the amount of force directed toward a person, i.e. a posterior force, during the first half of stance (Winter, 2005).

Pregnant fallers in our study displayed a greater braking impulse during ascent. This may be a reflection of a more cautious ascent strategy (Vanicek et al., 2010). This adaptation was not noted during descent.

The anteriorposterior and mediolateral distance between the whole-body CoM and the CoP during gait has been cited as a measure of gait stability (Mian et al., 2007), as has the sagittal plane and frontal plane CoM–CoP inclination angles (Lee and Chou, 2007). We previously noted that pregnant fallers have altered torso mechanics during gait when compared to pregnant non-fallers and non-pregnant controls (McCrory et al., 2012); thus, the 3D CoM–CoP distance and the sagittal and frontal plane CoM–CoP inclination angles may be altered. While the current study did not find a difference between fall groups in the amount of mediolateral CoP excursion, perhaps an examination of the linear and angular relationship of the CoP to the CoM would reveal an altered biomechanical pattern in pregnant fallers.

Older individuals with a history of falling display a larger peak braking force than non-fallers during stair locomotion (Vanicek et al., 2010). We did not see this alteration in our pregnant fallers and non-fallers; however, this may be attributed to the varied statistical techniques noted when comparing our study to others. For example, walking velocity, which is correlated to braking impulse (Messier et al., 1996), was handled differently in several studies on GRF variables during stair locomotion. Speed was not considered in the study by Bertucco and Cesari (Bertucco and Cesari, 2009). Hamel et al. standardized ascent and descent speeds to 0.65 m/s (Hamel et al., 2005). Although Vanicek and colleagues reported that older fallers descended more slowly than non-fallers, the effects of velocity on GRF variables was not considered in their statistical model (Vanicek et al., 2010). In our current study, ascent velocity was included as a covariate in the statistical analysis, and it was a significant factor in the braking force during ascent. If we had not included velocity in our statistical model, then pregnant fallers and non-fallers would have a larger braking force than controls (-0.072 BW vs -0.064 BW, respectively) ($P = 0.05$). The statistical processing technique, therefore, is an important consideration when drawing conclusions about a study's results.

We found several GRF variables to be different between pregnant fallers, pregnant non-fallers, and controls. During ascent, medial impulse was greater in pregnant fallers (-0.036 (0.015) BWs) compared to pregnant non-fallers (-0.031(0.015) BWs), which was also greater than controls (-0.023 (0.013) BWs). Step width during gait increases with pregnancy (Foti et al., 2000). Increasing step width is a common strategy to increase the base of support and thereby increase gait stability in individuals at risk for falling, such as the elderly and patients with Parkinson's disease (Cham et al., 2008; Owings and Grabiner, 2004). Because medial impulse is greater is pregnant fallers and stance time is not different between groups, then the medial GRF peak is likely greater in pregnant fallers. Paquette and Zhang reported a greater medial GRF peak in the presence of an increased step width during descent in older adults (Paquette and Zhang, 2012), thus it is likely that pregnant fallers increase their step width to increase their base of support and this increase stability during descent.

In both ascent and descent, the minimum between the peaks in the vertical GRF variables was larger in pregnant fallers compared to non-fallers. Our finding is supported by that of Bertucco and Cesari, who found the minimum between peaks to be larger in older individuals compared to young participants during stair locomotion (Bertucco and Cesari, 2009). The minimum between peaks occurs in midstance, a critical period during which the body must be stabilized in preparation for push-off (Bertucco and Cesari, 2009). Pregnant fallers may have reduced the upward acceleration of the CoM through midstance, which would increase the between peak minimum force, which would help to ensure a stable base so they could safely transition to the next stair during push-off.

The anterioposterior propulsive peak is a forward directed force that occurs in the latter half of stance, propelling a person forward during push-off (Winter, 2005). Normal stair descent involves a simultaneous lifting and horizontal translation of the body (McFadyen and Winter, 1988). As the body descends, the lower extremity musculature must control this landing by eccentrically allowing flexion of the ankle, knee, and hip, resulting in negative power at these joints (Startzell et al., 2000). During descent, anterioposterior propulsive peak was greater in pregnant non-fallers and controls than in pregnant fallers. Pregnant fallers may have displayed a smaller propulsive peak than pregnant non-fallers and controls in order to descend in a more controlled manner and allow gravity to lower them to the next step rather than pushing off in a forward direction and then having to exert greater eccentric control of the landing.

In our subject cohort, eight of the women classified as "pregnant fallers" reported falling once while pregnant. Five women fell twice and two fell three times (McCrory et al., 2010b). Thus, a total of 24 falls were reported during the study (McCrory et al., 2010b). Upon re-examination of the fall reports, we learned that four falls occurred during staircase locomotion, and all were during descent. Of the two subjects who reported falling three times, one said that she fell down the stairs twice. In both instances, she was wearing socks, not shoes, was carrying an older child whose age was approximately one year, and was in her second trimester. The other two falls were by two different women, each falling once. One woman stated that she was carrying a basket of laundry while barefoot in her third trimester. The other noted that she was wearing socks, was in her first trimester, and was not carrying anything when she fell. No subject was hospitalized for falling down the stairs, although bruising and soreness were reported. The data of these three women do not differ from the statistical mean of the pregnant fallers group.

Although only three of the 15 pregnant fallers reported falling on stairs, some interesting generalizations can be made. All of the falls occurred during descent. In the general population, more falls occur during descent than ascent (Tinetti et al., 1988). None of the women were wearing proper footwear at the time of the fall. Three of the falls occurred while the women were carrying something. Perhaps the CoM was shifted anteriorly during the task such that the women lost their balance, or perhaps their vision was occluded so that they could not see the stairs. We do not know if the women fell because they slipped or because they missed the stair, i.e. they may have over- or under-reached for the tread. The falls happened during each of the trimesters, so we cannot conclude that any one trimester may be more risky than another during descent.

The manner in which we categorized a pregnant woman as a "faller" or "non-faller" may be a limitation of the study in that a one-time fall may be more due to environmental or situational circumstances and may not represent the woman's true ability to control her body during staircase locomotion, and yet we still defined her as a "faller". We feel that if the falls were caused by random environmental or situational events, we would not see differences between "fallers" and "non-fallers" in the laboratory, and we therefore feel that our categorization strategy is correct.

Other limitations of this study should be addressed. Because subjects wore their own athletic shoes, differences in the structural support of the shoe may have introduced error into the data. Also, we do not have data on how many subjects, if any, touched the handrail for support during ascent or descent. Reid et al. noted that use of a handrail may alter GRF variables (Reid et al., 2011). It is our perception that only a few subjects may have used the handrail sporadically and lightly.

5. Conclusion

Pregnant fallers displayed several alterations to staircase locomotion compared to pregnant non-fallers and non-pregnant control women. Specifically, pregnant fallers had an increased anterioposterior braking impulse, medial impulse, and minimum between the vertical GRF peaks during ascent. During descent, pregnant fallers demonstrated a smaller anterioposterior propulsive peak, as well as a greater minimum between vertical GRF peaks, while the pregnant non-fallers had an increased propulsive impulse. Pregnant fallers and non-fallers demonstrated less mediolateral excursion of the CoP during descent than did control women. Pregnant fallers had a greater minimum between the vertical force peaks during both ascent and descent. During ascent, pregnant fallers demonstrated greater anterioposterior braking force; however, during descent, pregnant fallers had less anterioposterior propulsive force. These changes likely reflect a gait strategy intended to increase stability during staircase locomotion.

Conflict of interest

No author has any financial, personal, political, intellectual, or religious conflict of interest in this work.

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References

Bertucco, M., Cesari, P., 2009. Dimensional analysis and ground reaction forces for stair climbing: effects of age and task difficulty. Gait Posture 29, 326–331.
Calguneri, M., Bird, H.A., Wright, V., 1982. Changes in joint laxity occurring during pregnancy. Ann. Rheum. Dis. 41, 126–128.
Cham, R., Studenski, S.A., Perera, S., Bohnen, N.I., 2008. Striatal dopaminergic denervation and gait in healthy adults. Exp. Brain Res. 185, 391–398.
Dumas, G.A., Reid, J.G., Wolfe, L.A., Griffin, M.P., Mcgrath, M.J., 1995. Exercise, posture, and back pain during pregnancy.1. Exercise and posture. Clin. Biomech. 10, 98–103.
Dunning, K., Lemasters, G., Levin, L., Bhattacharya, A., Alterman, T., Lordo, K., 2003. Falls in workers during pregnancy: risk factors, job hazards, and high risk occupations. Am. J. Ind. Med. 44, 664–672.
Dunning, K., Lemasters, G., Bhattacharya, A., 2010. A major public health issue: the high incidence of falls during pregnancy. Matern. Child Health J. 14, 720–725.
Ersal, T., McCrory, J.L., Sienko, K.H., 2012. Characterizing Postural Stability in Pregnant Fallers and Non-fallers. Gait and Clinical Movement Analysis Society Annual Meeting. Grand Rapids, MI.
Foti, T., Davids, J.R., Bagley, A., 2000. A biomechanical analysis of gait during pregnancy. J. Bone Joint Surg. Am. Vol. 82A, 625–632.
Gilleard, W.L., Brown, J.M.M., 1996. Structure and function of the abdominal muscles in primigravid subjects during pregnancy and the immediate postbirth period. Phys. Ther. 76, 750–762.
Hamel, K.A., Okita, N., Bus, S.A., Cavanagh, P.R., 2005. A comparison of foot/ground interaction during stair negotiation and level walking in young and older women. Ergonomics 48, 1047–1056.
Kent, T., Gregor, J., Deardorff, L., Katz, V., 1999. Edema of pregnancy: a comparison of water aerobics and static immersion. Obstet. Gynecol. 94, 726–729.
Kim, D.H., 2009. A comparison of the center of pressure during stair descentin young and healthy elderly adults. J. Phys. Ther. Sci. 21, 129–131.
Lebrun, C.M., 1994. The effect of the phase of the menstrual-cycle and the birth-control pill on athletic performance. Clin. Sports Med. 13, 419–441.
Lee, H.J., Chou, L.S., 2007. Balance control during stair negotiation in older adults. J. Biomech. 40, 2530–2536.
Lymbery, J.K., Gilleard, W., 2005. The stance phase of walking during late pregnancy: temporospatial and ground reaction force variables. J. Am. Podiatr. Med. Assoc. 95, 247–253.
McCrory, J.L., Chambers, A.J., Daftary, A., Redfern, M.S., 2010a. Dynamic postural stability during advancing pregnancy. J. Biomech. 43, 2434–2439.
McCrory, J.L., Chambers, A.J., Daftary, A., Redfern, M.S., 2010b. Dynamic postural stability in pregnant fallers and non-fallers. BJOG 117, 954–962.
McCrory, J.L., Chambers, A.J., Daftary, A., Redfern, M.S., 2011. Ground reaction forces during gait in pregnant fallers and non-fallers. Gait Posture 43, 524–528.
McCrory, J.L., Chambers, A.J., Daftary, A., Redfern, M.S., 2012. Torso kinematics during gait differ between pregnant fallers and non-fallers. American Society of Biomechanics 2012 Annual Meeting. Gainesville, FL.
McCrory, J.L., Chambers, A.J., Daftary, A., Redfern, M.S., 2013. Ground reaction forces during stair locomotion in pregnancy. Gait Posture 38, 684–690.
Mcfadyen, B., Winter, D., 1988. An integrated biomechanical analysis of normal stair ascent and descent. J. Biomech. 21, 733–744.
Messier, S.P., Ettinger, W.H.J., Doyle, T.E., Morgan, T., James, M.K., O'Toole, M.L., Burns, R., 1996. Obesity: effects on gait in an osteoarthritic population. J. Appl. Biomech. 12, 161–172.
Mian, O.S., Narici, M.V., Minetti, A.E., Baltzopoulos, V., 2007. Centre of mass motion during stair negotiation in young and older men. Gait Posture 26, 463–469.
Owings, T.M., Grabiner, M.D., 2004. Variability of step kinematics in young and older adults. Gait Posture 20, 26–29.
Paquette, M., Zhang, S., 2012. Effects of increased step width on frontal plane joint mechanics in older adlts during stair descent. 2012 Annual Meeting of the Canadian Society of Biomechanics. Vancouver, BC.
Posthuma, B.W., Bass, M.J., Bull, S.B., Nisker, J.A., 1987. Detecting changes in functional ability in women with premenstrual-syndrome. Am. J. Obstet. Gynecol. 156, 275–278.
Reid, S.M., Novak, A.C., Brouwer, B., Costigan, P.A., 2011. Relationship between stair ambulation with and without a handrail and centre of pressure velocities during stair ascent and descent. Gait Posture 34, 529–532.
Startzell, J., Owens, D., Mulfinger, L., Cavanagh, P., 2000. Stair negotiation in older people: a review. J. Am. Geriatr. Soc. 48, 567–580.
Tinetti, M.E., Speechley, M., Ginter, S.F., 1988. Risk factors for falls among elderly persons living in the community. N. Engl. J. Med. 319, 1701–1707.
Tortora, G., Brabowski, S., 2000. Principles of Anatomy of Physiology. John Wiley & Sons, Inc., New York, NY.
Vanicek, N., Strike, S.C., Mcnaughton, L., Polman, R., 2010. Biomechanical differences during stair descent in fallers vs non-fallers. Parkinsonism Relat. Disord. 16, S76.
Verghese, J., Wang, C., Xue, X., Holtzer, R., 2008. Self-reported difficulty in climbing up or down stairs in nondisabled elderly. Arch. Phys. Med. Rehabil. 89, 100–104.
Winter, D., 2005. Kinetics: forces and moments of force, Biomechanics and Motor Control of Human MovementThird edition. John Wiley & Sons, Inc., Hoboken, NJ.
Wu, W.H., Meijer, O.G., Lamoth, C.J.C., Uegaki, K., Van Dieen, J.H., Wuisman, P.I.J.M., De Vries, J.I.P., Beek, P.J., 2004. Gait coordination in pregnancy: transverse pelvic and thoracic rotations and their relative phase. Clin. Biomech. 19, 480–488.
Yack, H., Chandran, R., Rao, S., Wilken, J., 2003. How normal hormonal fluctuations in women influence the biomechanics of stepping and cutting. J. Orthop. Sports Phys. Ther. 33, A28.