Gait & Posture 76 (2020) 270–276

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

An analysis of postpartum walking balance and the correlations to anthropometry

Sarah A. Rothwell[a], Chantel B. Eckland[a], Nigel Campbell[b], Christopher P. Connolly[a], Robert D. Catena[a,*]

[a] Department of Kinesiology and Educational Psychology, Washington State University, 101 Physical Education Building, Pullman, WA, United States
[b] Moscow/Pullman OBGYN, 1205 SE Professional Mall Blvd #102, Pullman, WA, United States

ARTICLE INFO

Keywords:
Dynamic balance
Postpartum
Gait
Anthropometry

ABSTRACT

Background: Falls caused by balance issues during pregnancy are quite common, and these issues can continue postpartum, potentially posing a danger to both the mother and baby. While there has been research on changes to walking gait during pregnancy, walking balance in the postpartum period has yet to be examined. Therefore, the aims of this study were to examine if balance changes persist in postpartum and the contribution of anthropometry changes.

Methods: This was done through longitudinal observational cohort study at 16 and 40 weeks gestation and at four-week intervals postpartum. Balance was measured as lateral center of mass motion during treadmill walking, and recorded with motion capture cameras following anthropometric measurements. Balance variables were statistically analyzed to observe how they changed over time. Hierarchical regression analyses determined correlations between balance and anthropometry.

Results: Balance was observed to improve significantly just following birth. Additionally, there were changes that continued to indicate improvement throughout the postpartum period. Anthropometry changes were significantly, but minimally, correlated with balance changes.

Significance: Many women begin to return to normal activities soon after birth. With women participating in various forms of exercise, potentially rigorous work requirements, and tasks around the home, it is important that they, their medical providers, and employers understand and consider the continued risks of imbalance.

1. Background

Walking is an integral part of everyday physical activity for pregnant and postpartum women [1]. Walking however, can pose more of a fall risk because of the many physical and physiological changes associated with pregnancy [2]. Even though pregnant women are returning to normal physical and work activities within a couple months after giving birth [3], there is currently no information about dynamic balance changes in the postpartum period.

As walking represents a real-world task in which falling is more common, dynamic balance change, as opposed to static balance, is particularly pertinent. Increasing dynamic imbalance during pregnancy has been identified by increasing center of pressure (COP) motion during force plate translational perturbations [4] and increasing lateral center of mass (COM) motion during level-walking analysis [5]. One possible reason for decreased balance is the three-dimensional shift in COM during pregnancy [6]. This is accompanied by swelling in the extremities [6,7], and greater lordotic lumbar curvature [8,9].

There is less information on dynamic balance postpartum. Lower extremity kinematic [10] and kinetic [11] studies by Branco et al. indicate that gait changes throughout pregnancy (mostly evident at the hip) mostly return to first trimester levels by 20 weeks postpartum [10]. The authors attribute much of the gait changes postpartum to body volume reductions [12]. However, these studies were limited to a single postpartum testing, so the actual change in postpartum are still unknown. Another study found postpartum women adopted a slower gait speed and shorter stride length compared to a control group, however, these women were also only tested once within 16–32 weeks after birth, providing no longitudinal data on gait characteristics in the postpartum period [13].

We have recently published longitudinal findings of anthropometry changes through several months postpartum, some of which immediately change following birth and others that gradually revert through postpartum [9]. No studies have yet examined dynamic

* Corresponding author at: 113F Smith Gym, Washington State University, Pullman, WA, United States.
E-mail address: robert.catena@wsu.edu (R.D. Catena).

https://doi.org/10.1016/j.gaitpost.2019.12.017
Received 10 June 2019; Received in revised form 8 December 2019; Accepted 13 December 2019
0966-6362/

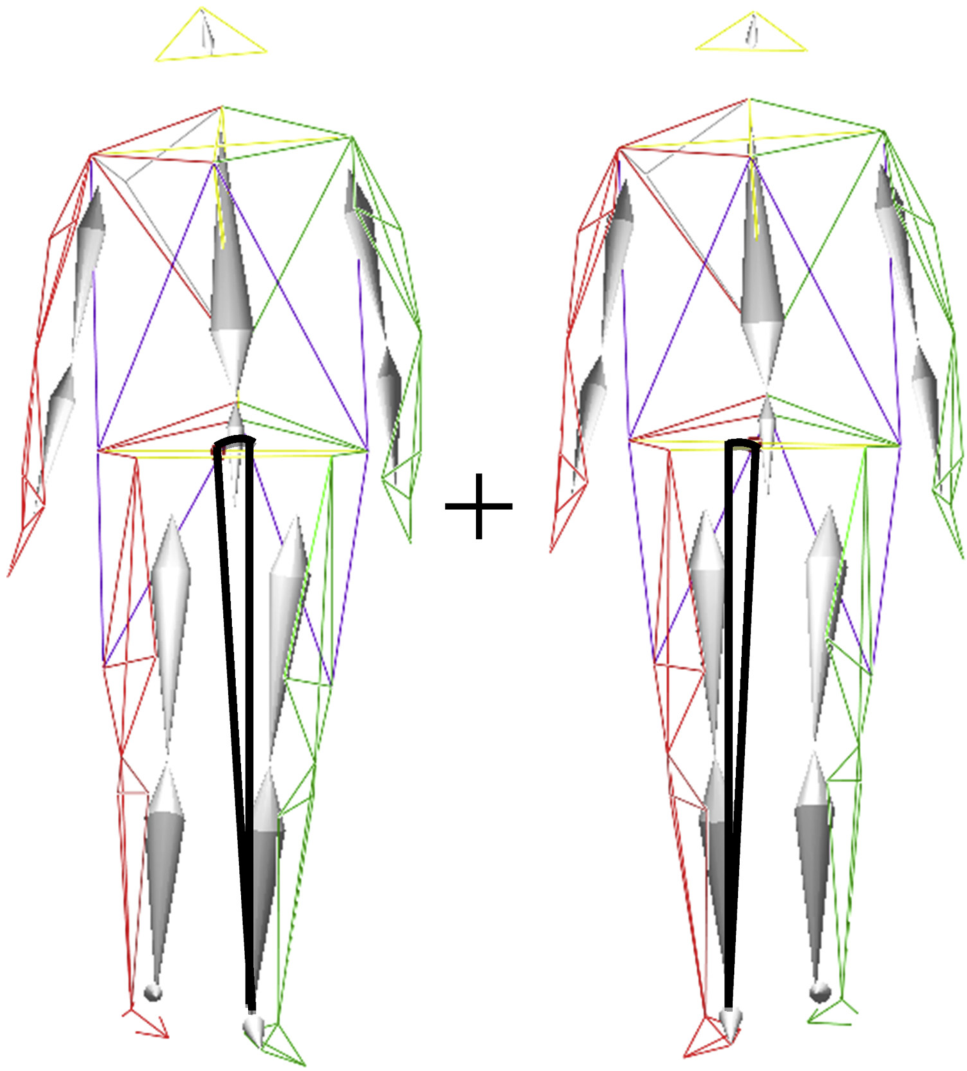

Fig. 1. ML Angle variable is the total angular range of motion of the body COM around the ankle joint centers, around the left ankle (left side of figure) plus around the right ankle (right side of figure).

balance during gait through the postpartum period. The first goal of this study was to determine if dynamic balance changes immediately following birth, over a period of time postpartum, or if balance issues that occur during pregnancy remain following birth. We hypothesized that there would still be imbalance persisting into the postpartum period. The second goal of this study was to determine how anthropometry changes correlate with balance changes postpartum. We hypothesized that anthropometry is highly correlated to balance changes postpartum as compared to during pregnancy.

2. Methods

Seventeen participants completed two pregnancy testings at 16–20 weeks gestation and 36–40 weeks gestation. Within a month following birth, they returned to complete seven more testings in 4-week intervals to 28 weeks postpartum. Participants ranged in age from 22 to 37 years old at the start of testing. They were all free of injuries and neurological conditions that could impact balance, and women with high-risk pregnancies were not included. Approval for working with human participants was granted by the Washington State University Institutional Review Board.

2.1. Experimental procedures

Before each testing, participants signed an informed consent form. All participants wore similar clothing of a tank top, shorts, and their own walking shoes. Testing started with anthropometry measurements of 13 body segments (head, arms, forearms, torso, pelvis, thighs, shanks, feet) [6].These data were used to calculate volumes of segments, and with assumed densities, calculation of segment specific masses [14]. Outlier anthropometrics were rechecked as previously described [6].

Following anthropometric measurements, 54 markers were placed at anatomical landmarks using a full-body 13-segment markerset previously described [9]. Ten motion capture cameras (MotionAnalysis Corp., Santa Rosa, CA) recorded marker movement at 100 Hz while participants performed directed tasks. The first and last tasks were a quiet standing and laying, respectively, for ten seconds on force plates (Kistler Inc., Amherst, NY) collecting at 1000 Hz. This allowed for joint center identification, using virtual markers, during walking trials when medial markers were removed from the ankles, knee, and elbows. These two trials also allowed calculations of the person-specific torso COM location from force plate COP data: standing trial used for anterior-posterior COM and laying trial used for mediolateral and vertical COM [6]. In between standing and laying trials, women were asked to walk on a treadmill (Lifespan Inc., Providence, RI) and incrementally

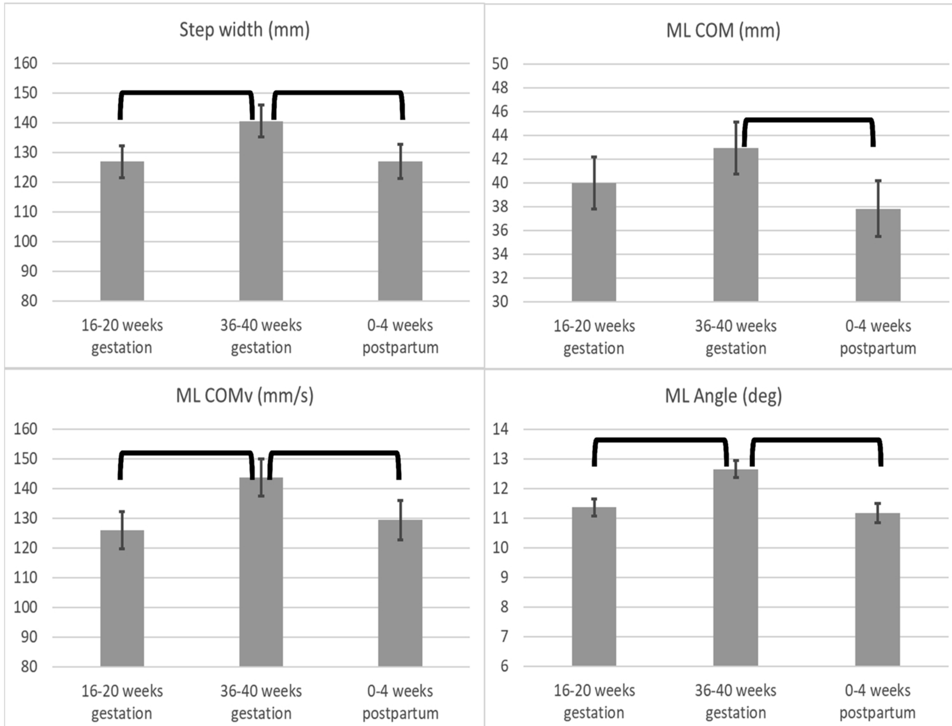

Fig. 2. Average balance values from pregnancy to postpartum. Error bars are standard errors. Significant pairwise comparisons ($p \le 0.05$) between time points are indicated by a crossbar.

increased the speed until they reached a self-selected "comfortable" pace. Once a speed was selected, we reassessed their comfort after 60 s of practice walking. Once they had practiced with a "comfortable" speed for 60 s and wanted to maintain it, we then recorded kinematic data for 60 s.

2.2. Data processing procedures

Marker data were smoothed with a 6 Hz 4^{th} order low-pass Butterworth filter [15]. A custom Matlab (Mathworks Inc., Natick, MA) program calculated participant-specific segment masses and centers of mass as previously documented [6]. Body COM data were calculated in Cortex Biosuite (MotionAnalysis Corp., Santa Rosa, CA) as the weighted sum of 13 body segments. Gait cycles were separated at right heal strike yielding a minimum of 37 gait cycles for each testing. For each gait cycle, custom Matlab (Mathworks Inc., Natick, MA) program calculated four dynamic balance variables: step width as the maximum lateral difference between right and left ankle joint centers over the stride, linear range of medial-lateral COM motion (ML COM) over the stride, the maximum medial-lateral COM velocity (ML COMv) during the stride, and medial-lateral angular range of motion of the COM around the ankle joint center (ML Angle) shown in Fig. 1. These four variables have been previously used to uniquely quantify balance changes during pregnancy [5], with greater values specifically in the lateral direction indicating poorer balance based on studies of other patient populations [16–18]. Variables were then averaged across the gait cycles.

2.3. Statistical analysis

Statistical analyses were performed using the SPSS v24 Statistics software (IBM Corp., Armonk, NY). Balance data described above were statistically measured using two linear mixed model (one-way repeated measures) tests, with follow-up *Bonferroni* pairwise comparisons. Testing time was the independent variable. The first statistical analysis was conducted between all nine testing times (two during pregnancy and seven postpartum). To account for the potential that pregnancy related balance changes and the additional comparisons would overwhelm any statistically significant postpartum changes, the second statistical analysis was conducted only between the seven monthly postpartum testings. Statistical significance was determined using an alpha level of 0.05.

We have previously reported on anthropometry changes from pregnancy to postpartum [9]. We found that body mass index (BMI), breast-level torso width (BreastW), breast-level torso depth (BreastD), L3-4-level torso width (L34W), greater trochanter-level circumference (GTC), three-dimensional torso center of mass position (tCOM), anterior-posterior and mediolateral body center of mass position (bCOM), standing hip extension posture (HipE), and lumbar extension (LumbarE) to significantly change during the first twenty-eight weeks postpartum. Given these changes, we performed four hierarchical regressions on each dependent balance variable to determine how these anthropometry variables were correlated with dynamic balance measures. The four models were with and without balance data during pregnancy and with and without covariates. The order of our hierarchical analyses with covariates was intentionally chosen *a priori* to consider covariates first, and then anthropometric variables above were considered. We considered potential covariates to the dependent variables examined here in forward step order that input into the model in order of significance, with any value not reaching significance ($p > 0.05$) not inserted into the model. Preferred walking speed, body height, participant age, and gestational week/postpartum week were covariates. The second step in our hierarchical regression was to consider the anthropometric factors of particular interest in this study. These variables were also entered in forward step order that inputs into the model in order of significance. We then performed the regression analysis with just the second step above (without covariates entered first) to determine how much variance in balance dependent anthropometry variables alone explained.

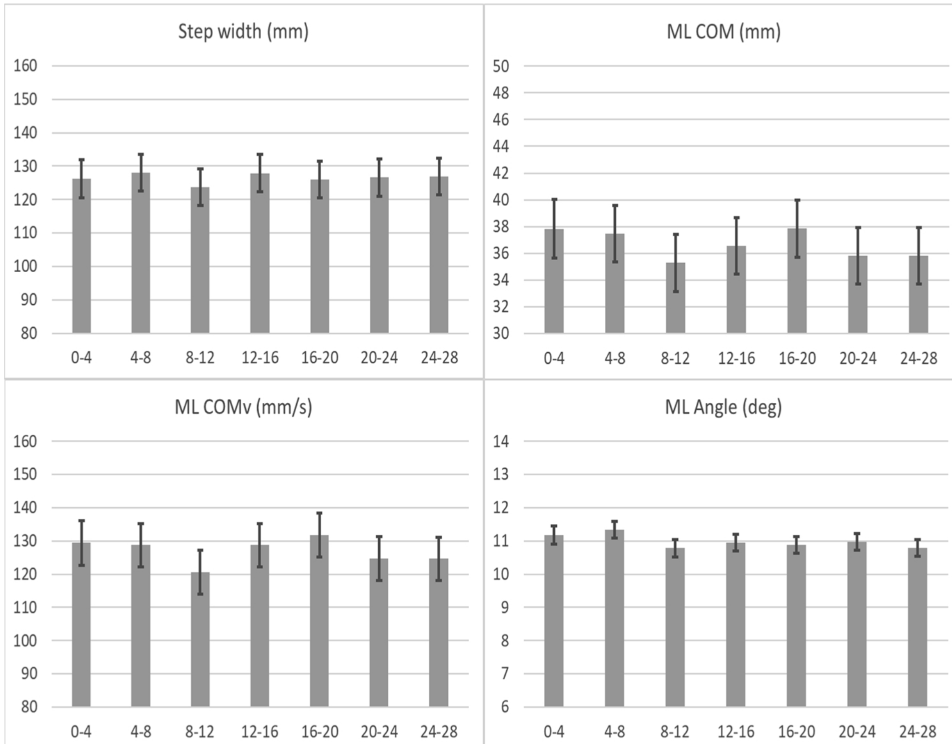

Fig. 3. Average balance values throughout postpartum. Error bars are standard errors. Significant pairwise comparisons ($p \leq 0.05$) between time points are indicated by a crossbar. X-axis is the range in weeks postpartum for each testing.

3. Results

3.1. Balance change between pregnancy and postpartum (time points 1, 2 and 3)

Step width significantly increased by 11 % through pregnancy ($p = 0.001$) and then immediately decreased by 11 % at four weeks after birth ($p = 0.009$) (Fig. 2). ML COM motion increased slightly (8 %) during pregnancy, but was reduced by more than 13 % after birth ($p = 0.015$). ML COMv significantly increased by 14 % through pregnancy ($p < 0.001$) and then immediately decreased by 11 % after birth ($p = 0.029$). ML Angle significantly increased by 11 % through pregnancy ($p < 0.001$) and then immediately decreased by 13 % ($p < 0.001$).

3.2. Balance changes throughout postpartum (time points 3 through 9)

Step width did not significantly change throughout the postpartum period ($p = 0.333$) (Fig. 3). The other three balance measures had significant main effects of time and appeared to decrease by the 8–12 week postpartum testing, but there were no pairwise significant differences to confirm this. ML COM motion decreased by 6 % between first and last postpartum testings, with a significant main effect of time ($p = 0.010$). ML COMv decreased by 4 % between first and last postpartum testings, with a significant main effect of time ($p = 0.010$). ML Angle gradually decreased by 4 % between first and last postpartum testings, with a significant main effect of time ($p = 0.048$).

3.3. Correlation between anthropometry and balance

Collinearity between anthropometry variables was low with all variance inflation factors, less than 4.0. The step width regression model with the most explained variance was without pregnancy data and with covariates (Table 1). Almost half of the variance in step width was accounted for in this model. Step width was most correlated with preferred walking speed. The only anthropometric factor step width was correlated to in all four models was HipE. BMI did not get entered into any of the four models, indicating that BMI did not significantly explain any unique variance in step width compared to other covariates.

Preferred walking speed and age of the participant at testing were also most correlated with ML COM linear motion (Table 2). Interestingly, without covariates, only trunk COM accounted for the significant explained variance in the regression analyses: ML trunk COM position correlated with pregnancy ML COM, and AP trunk COM position correlated with postpartum ML COM. No covariates were significantly correlated to maximum COM velocity in the ML direction (Table 3). This could indicate ML COMv as a better (independent) indicator of pregnancy and postpartum balance changes.

The regression model for ML Angle was clearly improved with pregnancy data (Table 4), indicating this variable to be more indicative of pregnancy balance changes than postpartum balance changes. Time (gestational and postpartum) was only entered once in all regression analyses, for ML Angle with pregnancy data. HipC and LumbarE were entered in all four analyses on ML Angle.

4. Discussion

The first goal of this research was to determine the duration into the postpartum period of balance changes that occur during a typical pregnancy. No known studies have explored dynamic balance changes following a pregnancy. This is especially of interest because the typical U.S. woman is granted only 12 weeks of unpaid leave from a job following her pregnancy as part of the 1993 Family and Medical Leave Act [19]. It is important to recognize that some women may still need additional precautions past the 12 week leave period, as they transition back into everyday physical and work activities, even though much of the added anterior torso mass is gone.

Dynamic (gait) balance change throughout pregnancy has been examined in greater depth by a couple of previous studies, where mediolateral COM excursion [5], mediolateral COM velocity [5], and

Table 1
Hierarchical multiple regression model summary for step width.

Model	independent variable	β	R	R^2	ΔR^2	P	VIF
With pregnancy data and covariates	1. Speed	0.043	0.450	0.203		< 0.001	1.000
	2. AP tCOM	55.595	0.515	0.266	0.063	0.002	1.022
	3. HipE	0.617	0.562	0.316	0.050	0.003	1.164
	4. ML tCOM	105.640	0.583	0.340	0.025	0.035	1.034
	5. LumbarE	0.406	0.606	0.367	0.027	0.027	1.074
With pregnancy data and without covariates	1. LumbarE	0.518	0.215	0.046		0.015	1.000
	2. AP tCOM	46.098	0.300	0.090	0.044	0.017	1.014
	3. HipE	0.655	0.381	0.145	0.055	0.006	1.188
	4. L34W	−173.692	0.418	0.175	0.029	0.040	1.078
	5. BreastD	399.337	0.454	0.206	0.032	0.031	3.048
Without pregnancy data and with covariates	1. Speed	78.661	0.542	0.293		< 0.001	1.000
	2. Age	−1.541	0.581	0.337	0.044	0.017	1.009
	3. AP tCOM	58.312	0.624	0.389	0.052	0.007	1.068
	4. HipE	0.607	0.663	0.440	0.051	0.006	1.100
	5. LumbarE	0.429	0.683	0.467	0.026	0.041	1.105
Without pregnancy data and without covariates	1. HipE	0.771	0.302	0.091		0.003	1.000
	2. LumbarE	0.629	0.389	0.151	0.60	0.013	1.041

β is the unstandardized regression coefficient. R is the partial correlation coefficient. $R^2$is unadjusted explained variance. ΔR^2 is change in explained variance from the last step. P is the significance of the F value change between steps. Variance inflation factor (VIF) is reported to account for collinearity.

mediolateral COM angular motion [5,20] to increase significantly between 16 weeks and the third trimester. The separate sample of participants in this current study followed the same balance trends with all balance variables increasing (indicative of poorer balance) between 16 weeks and late in pregnancy, indicating that participants had less ability to control dynamic balance as pregnancy progressed [5]. Larger ML linear motion [17] and ML ankle angle [21] can be associated with imbalance and waddling type gait [22]. Foti et al., however, suggest waddling gait may be countered by joint kinematic changes [23].

All balance measures improved significantly between the last month of pregnancy and the first month postpartum. However, other than step width, measures of balance continued to improve slightly within the 7 months of postpartum testing. First, this leads us to believe step width is unique from other COM balance measures. Step width can be either altered consciously as a perception of balance ability [24] or reactive correction to instantaneous imbalance [25,26]. As we did not initiate imbalance in this study, we believe observed step width changes were related to perception of balance for pregnant and postpartum women. This was further supported by our finding that step width was correlated most with walking speed (another indicator of conservative gait) rather than anthropometry. It could be the case that pregnant women have no change in perception of (im)balance through the postpartum period even if there are actual balance changes, but our current study design did not allow us to specifically examine this. On the other hand, there was a continued decrease in mediolateral center of mass motion in the postpartum period, indicating that balance continued to improve throughout postpartum, and possibly indicating participants continued to experience slight imbalance early in postpartum. However, as compared to a previous study of healthy young adults [27], all postpartum values of ML COM and ML COMv for our participants indicate better balance. We've previously suggested that our participants' physical activity may contribute to unique findings [28], but our studies to date cannot distinguish population vs. methodology reasons for balance differences compared to other studies. Future studies should explore postpartum changes more with known fallers as done by one previous pregnancy study [29].

The second goal of this research was to determine the correlation between anthropometry and balance postpartum. We had previously described only a minimal correlation between anthropometry and balance during pregnancy [30]. Our previous study resulted in a total explained variance between pregnancy anthropometry and ML COMv of 0.097 and ML Angle of 0.170 [30]. Our current findings suggest slightly improved, but still small correlations postpartum. This current study resulted in explained variance of 0.181 and 0.258 for those same two variables, respectively. The most commonly observed variables to have a correlation to balance measures in this study were lumbar extension posture (LumbarE) and the torso AP COM position (AP tCOM). Based on our previous study, AP tCOM moves back to a typical nonpregnant position further into postpartum (as to be expected with loss of anterior abdominal mass), but LumbarE continues to gradually increase (more lordotic curvature) through pregnancy and during postpartum [9]. Both of these variables had a positive correlation to more walking imbalance in the current study, potentially indicating that alignment of the COM posteriorly, over the hips, to be advantageous to balance control. This has previously been suggested for standing balance control in pregnancy [8], but our current study is the first that we

Table 2
Hierarchical multiple regression model summary for ML COM.

Model	independent variable	β	R	R^2	ΔR^2	P	VIF
With pregnancy data and covariates	1. Speed	−0.024	0.625	0.391		< 0.001	1.000
	2. Age	−0.375	0.646	0.417	0.026	0.021	1.003
	3. Body height	0.238	0.672	0.452	0.035	0.006	1.133
	4. AP tCOM	13.513	0.688	0.473	0.456	0.029	1.077
With pregnancy data and without covariates	1. ML bCOM	0.247	0.208	0.043		0.019	1.000
Without pregnancy data and with covariates	1. Speed	−0.021	0.565	0.319		< 0.001	1.000
	2. Age	−0.450	0.602	0.362	0.043	0.016	1.009
	3. Body height	0.263	0.642	0.412	0.050	0.007	1.119
	4. AP tCOM	23.080	0.685	0.469	0.057	0.003	1.069
Without pregnancy data and without covariates	1. AP tCOM	22.287	0.238	0.057		0.022	1.000

β is the unstandardized regression coefficient. R is the partial correlation coefficient. $R^2$is unadjusted explained variance. ΔR^2 is change in explained variance from the last step. P is the significance of the F value change between steps. Variance inflation factor (VIF) is reported to account for collinearity.

Table 3
Hierarchical multiple regression model summary for ML COMv.

Model	independent variable	β	R	R^2	ΔR^2	P	VIF
With pregnancy data and covariates	1. AP tCOM	80.139	0.310	0.096		< 0.001	1.000
	2. LumbarE	0.680	0.391	0.153	0.057	0.005	1.014
With pregnancy data and without covariates	1. AP tCOM	80.139	0.310	0.096		< 0.001	1.000
	2. LumbarE	0.680	0.391	0.153	0.057	0.005	1.014
Without pregnancy data and with covariates	1. AP tCOM	93.028	0.323	0.105		0.002	1.000
	2. LumbarE	0.806	0.426	0.181	0.077	0.005	1.001
Without pregnancy data and without covariates	1. AP tCOM	93.028	0.323	0.105		0.002	1.000
	2. LumbarE	0.806	0.426	0.181	0.077	0.005	1.001

β is the unstandardized regression coefficient. R is the partial correlation coefficient. $R^2$is unadjusted explained variance. ΔR^2 is change in explained variance from the last step. P is the significance of the F value change between steps. Variance inflation factor (VIF) is reported to account for collinearity.

know of to also suggest this for mediolateral dynamic balance during postpartum.

Another interesting finding from our correlation analyses is there appears to be different significant correlates to postpartum balance compared to pregnancy. We have previously reported increased mass remains around the pelvis, torso, and breast levels for postpartum mothers who are breastfeeding, which could contribute to COM changes postpartum [9]. Additionally, high levels of relaxin remain in the body for about 5–6 weeks after birth [31], which may also contribute to change in COM motion. Fatigue and depression are common postpartum cognitive impediments [32]. Neurological and physical changes within the back and lower extremities are also commonly experienced postpartum [33]. These factors represent fluctuating changes within our postpartum testing period that could have affected balance changes.

Pregnancy has also been known to cause lasting arch height reductions [34], urinary retention problems [35], type 2 diabetes (from gestational diabetes) [36], diastasis recti abdominis [37], and many persistent physical changes [9,38]. These changes could pose additional problems for postpartum balance, but also during a multigravida pregnancy. Since our study sample included eleven primigravida and six multigravida women, and our multigravida sample is insufficiently small and diverse (ranging between 2nd and 5th pregnancies) to take into account these group differences, follow-up studies will be required to understand the extent to which lasting effects from previous pregnancies affect balance. Further complicating balance for postpartum women is that they will often carry their infant. Some previous research has been conducted on the musculoskeletal effects of infant carrying position [39], and the balance effects of load carrying [40]. Presumably, comfort and economic factors are paramount in infant carrying device consideration. Future studies should investigate the effects of postpartum infant carrying on balance control for the safety of mother and child.

Our balance findings support current physical activity recommendations [41] that women without any complications surrounding the birth may begin gradually increasing to a similar level at which they participated in during pregnancy within about four weeks postpartum. However, some balance and fall precautions may be important for women returning to work following birth, especially in more physically demanding jobs. Time (gestational and postpartum) was only entered once in all regression analyses, for ML Angle during pregnancy. This seems to indicate that postpartum balance changes typically have very little to do with the amount of time following birth. Instead, individual-specific pregnancy and postpartum changes are a more significant correlate to balance, and predefining a time to return to normal activities should be avoided. Accommodations may be advisable for postpartum workers, as many women return to work within the time frame of this study [3]. Healthcare providers play a vital role in enabling women to gain accommodations at work, so it is important that they understand that balance is unrelated to time after pregnancy.

5. Conclusion

Findings from this study support significant balance improvement immediately following birth, but also the presence of slight balance change in early in the postpartum period. It appears that while postpartum balance is slightly more correlated to anthropometric changes than balance during pregnancy, there continue to be other factors that contribute significantly more to balance changes. Some postpartum women may need continued precautions for several months following pregnancy as they transition back into typical daily activities.

Table 4
Hierarchical multiple regression model summary for ML Angle.

Model	independent variable	β	R	R^2	ΔR^2	P	VIF
With pregnancy data and covariates	1. Speed	−0.001	0.267	0.071		0.002	1.000
	2. Time	−0.017	0.327	0.107	0.035	0.029	1.073
	3. Body height	−0.034	0.380	0.144	0.037	0.022	1.085
	4. HipC	8.793	0.522	0.273	0.129	< 0.001	1.128
	5. LumbarE	0.039	0.584	0.341	0.068	0.001	1.180
	6. AP tCOM	3.083	0.631	0.398	0.057	0.001	1.066
	7. ML tCOM	5.953	0.647	0.419	0.021	0.042	1.204
With pregnancy data and without covariates	1. HipC	10.357	0.449	0.201		< 0.001	1.000
	2. AP tCOM	3.292	0.518	0.269	0.068	0.001	1.024
	3. LumbarE	0.030	0.562	0.316	0.048	0.004	1.016
	4. ML tCOM	8.212	0.599	0.359	0.043	0.005	1.108
Without pregnancy data and with covariates	1. Body height	−0.030	0.223	0.050		0.031	1.000
	2. HipC	5.984	0.380	0.144	0.094	0.002	1.107
	3. LumbarE	0.041	0.510	0.260	0.116	< 0.001	1.076
Without pregnancy data and without covariates	1. HipC	6.693	0.361	0.130		< 0.001	1.000
	2. LumbarE	0.042	0.508	0.258	0.128	< 0.001	1.025

β is the unstandardized regression coefficient. R is the partial correlation coefficient. $R^2$is unadjusted explained variance. ΔR^2 is change in explained variance from the last step. P is the significance of the F value change between steps. Variance inflation factor (VIF) is reported to account for collinearity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by a WSU New Faculty Seed grant and a College of Education Faculty award.

References

[1] M. DeMaio, E.F. Magann, Exercise and pregnancy, J. Am. Acad. Orthop. Surg. 17 (8) (2009) 504–514.
[2] K. Dunning, G. Lemasters, A. Bhattacharya, A major public health issue: the high incidence of falls during pregnancy, Matern. Child Health J. 14 (5) (2010) 720–725.
[3] ACOG Committee Opinion No. 733: employment considerations during pregnancy and the postpartum period, Obstet. Gynecol. 131 (4) (2018) e115–e123.
[4] J.L. McCrory, A.J. Chambers, A. Daftary, M.S. Redfern, Dynamic postural stability during advancing pregnancy, J. Biomech. 43 (12) (2010) 2434–2439.
[5] D. Flores, C.P. Connolly, N. Campbell, R.D. Catena, Walking balance on a treadmill changes during pregnancy, Gait Posture 66 (2018) 146–150.
[6] R.D. Catena, C.P. Connolly, K.M. McGeorge, N. Campbell, A comparison of methods to determine center of mass during pregnancy, J. Biomech. 11 (71) (2018) 217–224.
[7] J.W. Blaszczyk, A. Opala-Berdzik, M. Plewa, Adaptive changes in spatiotemporal gait characteristics in women during pregnancy, Gait Posture 43 (2016) 160–164.
[8] K.K. Whitcome, L.J. Shapiro, D.E. Lieberman, Fetal load and the evolution of lumbar lordosis in bipedal hominins, Nature 450 (7172) (2007) 1075–1078.
[9] R.D. Catena, N. Campbell, W.C. Wolcott, S.A. Rothwell, Anthropometry, standing posture, and body center of mass changes up to 28 weeks postpartum in Caucasians in the United States, Gait Posture 70 (2019) 196–202.
[10] M.A. Branco, R. Santos-Rocha, F. Vieira, L. Aguiar, A.P. Veloso, Three-dimensional kinematic adaptations of gait throughout pregnancy and post-partum, Acta Bioeng. Biomech. 18 (2) (2016) 153–162.
[11] M. Branco, R. Santos-Rocha, F. Vieira, L. Aguiar, A.P. Veloso, Three-dimensional kinetic adaptations of gait throughout pregnancy and postpartum, Scientifica (Cairo) 2015 (2015) 580374.
[12] M. Branco, R. Santos-Rocha, F. Vieira, M.R. Silva, L. Aguiar, A.P. Veloso, Influence of body composition on gait kinetics throughout pregnancy and postpartum period, Scientifica (Cairo) 2016 (2016) 3921536.
[13] J. Bertuit, V. Feipel, M. Rooze, Temporal and spatial parameters of gait during pregnancy, Acta Bioeng. Biomech. 17 (2) (2015) 93–101.
[14] M.J. Pavol, T.M. Owings, M.D. Grabiner, Body segment inertial parameter estimation for the general population of older adults, J. Biomech. 35 (5) (2002) 707–712.
[15] B. Yu, D. Gabriel, L. Noble, K.-N. An, Estimate of the optimum cutoff frequency for the butterworth low-pass digital filter, J. Appl. Biomech. 15 (1999) 319–329.
[16] C.J. Chen, L.S. Chou, Center of mass position relative to the ankle during walking: a clinically feasible detection method for gait imbalance, Gait Posture 31 (3) (2010) 391–393.
[17] L.S. Chou, K.R. Kaufman, M.E. Hahn, R.H. Brey, Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance, Gait Posture 18 (3) (2003) 125–133.
[18] P. Silsupadol, V. Lugade, A. Shumway-Cook, P. van Donkelaar, L.S. Chou, U. Mayr, et al., Training-related changes in dual-task walking performance of elderly persons with balance impairment: a double-blind, randomized controlled trial, Gait Posture 29 (4) (2009) 634–639.
[19] United States. Department of L, The Family and Medical Leave Act of 1993, U.S. Dept. of Labor, Washington, D.C, 1993.
[20] Z. Krkeljas, Changes in gait and posture as factors of dynamic stability during walking in pregnancy, Hum. Mov. Sci. 58 (2018) 315–320.
[21] T. Chen, L.S. Chou, Altered center of mass control during sit-to-walk in elderly adults with and without history of falling, Gait Posture 38 (4) (2013) 696–701.
[22] J.L. McCrory, A.J. Chambers, A. Daftary, M.S. Redfern, The pregnant "waddle": an evaluation of torso kinematics in pregnancy, J. Biomech. 47 (12) (2014) 2964–2968.
[23] T. Foti, J.R. Davids, A. Bagley, A biomechanical analysis of gait during pregnancy, J. Bone Joint Surg. Am. 82 (5) (2000) 625–632.
[24] O.A. Donoghue, H. Cronin, G.M. Savva, C. O'Regan, R.A. Kenny, Effects of fear of falling and activity restriction on normal and dual task walking in community dwelling older adults, Gait Posture 38 (1) (2013) 120–124.
[25] L. Hak, H. Houdijk, F. Steenbrink, A. Mert, P. van der Wurff, P.J. Beek, et al., Speeding up or slowing down?: gait adaptations to preserve gait stability in response to balance perturbations, Gait Posture 36 (2) (2012) 260–264.
[26] S. Sivakumaran, A. Schinkel-Ivy, K. Masani, A. Mansfield, Relationship between margin of stability and deviations in spatiotemporal gait features in healthy young adults, Hum. Mov. Sci. 57 (2018) 366–373.
[27] M. Arvin, M. Mazaheri, M.J.M. Hoozemans, M. Pijnappels, B.J. Burger, S.M.P. Verschueren, et al., Effects of narrow base gait on mediolateral balance control in young and older adults, J. Biomech. 49 (7) (2016) 1264–1267.
[28] R.D. Catena, J.P. Bailey, N. Campbell, H.E. Music, Stand-to-sit kinematic changes during pregnancy correspond with reduced sagittal plane hip motion, Clin. Biomech. (Bristol, Avon) 67 (2019) 107–114.
[29] J.L. McCrory, A.J. Chambers, A. Daftary, M.S. Redfern, Dynamic postural stability in pregnant fallers and non-fallers, BJOG 117 (8) (2010) 954–962.
[30] R.D. Catena, N. Campbell, A.L. Werner, K.M. Iverson, Anthropometric changes during pregnancy provide little explanation of dynamic balance changes, J. Appl. Biomech. 35 (3) (2019) 232–239.
[31] M.L. Marnach, K.D. Ramin, P.S. Ramsey, S.W. Song, J.J. Stensland, K.N. An, Characterization of the relationship between joint laxity and maternal hormones in pregnancy, Obstet. Gynecol. 101 (2) (2003) 331–335.
[32] N. Wilson, J.J. Lee, B. Bei, Postpartum fatigue and depression: a systematic review and meta-analysis, J. Affect. Disord. 246 (2019) 224–233.
[33] A. Gutke, H.C. Ostgaard, B. Oberg, Predicting persistent pregnancy-related low back pain, Spine (Phila Pa 1976) 33 (12) (2008) E386–393.
[34] N.A. Segal, E.R. Boyer, P. Teran-Yengle, N.A. Glass, H.J. Hillstrom, H.J. Yack, Pregnancy leads to lasting changes in foot structure, Am. J. Phys. Med. Rehabil. 92 (3) (2013) 232–240.
[35] A. Tiberon, M. Carbonnel, A. Vidart, M. Ben Halima, X. Deffieux, J.M. Ayoubi, Risk factors and management of persistent postpartum urinary retention, J. Gynecol. Obstet. Hum. Reprod. 47 (9) (2018) 437–441.
[36] J. Guo, J.L. Chen, R. Whittemore, E. Whitaker, Postpartum lifestyle interventions to prevent type 2 diabetes among women with history of gestational diabetes: a systematic review of randomized clinical trials, J. Womens Health (Larchmt) 25 (1) (2016) 38–49.
[37] S. Barbosa, R.A. de Sa, L.G. Coca Velarde, Diastasis of rectus abdominis in the immediate puerperium: correlation between imaging diagnosis and clinical examination, Arch. Gynecol. Obstet. 288 (2) (2013) 299–303.
[38] P. Ponnapula, J.S. Boberg, Lower extremity changes experienced during pregnancy, J. Foot Ankle Surg. 49 (5) (2010) 452–458.
[39] C.Y. Wu, H.R. Huang, M.J. Wang, Baby carriers: a comparison of traditional sling and front-worn, rear-facing harness carriers, Ergonomics 60 (1) (2017) 111–117.
[40] R.D. Catena, A. DiDomenico, J.J. Banks, J.T. Dennerlein, The effect of load weight on balance control during lateral box transfers, Ergonomics 53 (11) (2010) 1359–1367.
[41] A.B. Roy, Postpartum exercise, ACSM Health Fitness J. 18 (6) (2014) 3–4.