Gait & Posture 39 (2014) 218–223

Contents lists available at ScienceDirect

Gait & Posture

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

Theoretical and experimental indicators of falls during pregnancy as assessed by postural perturbations

Tulga Ersal [a], Jean L. McCrory [b,c], Kathleen H. Sienko [a,d,*]

[a] Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA
[b] Division of Exercise Physiology, Department of Human Performance and Applied Exercise Science, West Virginia University, Morgantown, WV, USA
[c] Department of Health and Physical Activity, University of Pittsburgh, Pittsburgh, PA, USA
[d] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI, USA

ARTICLE INFO

Article history:
Received 5 October 2012
Received in revised form 3 July 2013
Accepted 9 July 2013

Keywords:
Pregnancy
Falls
Balance
Mathematical modeling
Perturbations

ABSTRACT

Throughout pregnancy, women experience physical, physiological, and hormonal alterations that are often accompanied by decreased postural control. According to one study, nearly 27% of pregnant women fell while pregnant. This study had two objectives: (1) to characterize the postural responses of pregnant fallers, nonfallers, and controls to surface perturbations, and (2) to develop a mathematical model to gain insights into the postural control strategies of each group. This retrospective analysis used experimental data obtained from 15 women with a fall history during pregnancy, 14 women without a fall history during pregnancy, and 40 nonpregnant controls. Small, medium, and large translational support surface perturbations in the anterior and posterior directions were performed during the pregnant participants' second and third trimesters. A two-segmented mathematical model of bipedal stance was developed and parameterized, and optimization tools were used to identify ankle and hip stiffness, viscosity, and the feedback time delay by searching for the best fits to experimental COP data. The peak differences between the center of pressure and center of gravity (COP-COG) values were significantly smaller for the pregnant fallers compared with the pregnant nonfallers and controls ($p < 0.01$). Perturbation magnitude was a significant factor ($p < 0.01$), but perturbation direction was not ($p = 0.24$). Model fits were obtained with a mean goodness of fit value of $R^2 = 0.92$. Theoretical results indicated that pregnant nonfallers had higher ankle stiffness compared with the pregnant fallers and the controls, which suggests that ankle stiffness itself may be the dominant reason for the different dynamic response characteristics (e.g., peak COP–COG) observed. We conclude that increasing ankle stiffness could be an important strategy to prevent falling by pregnant women.

1. Introduction

As pregnancy advances, women undergo various physical, physiological, and hormonal alterations. For example, they typically gain 11–16 kg in weight [1]. These weight gains are primarily concentrated in the abdominal region and can increase lumbar lordosis [2]. Hormonal fluctuations can increase ligamentous laxity [3,4], and changes in plantar foot pressures are observed [5]. Such alterations can lead to balance problems. According to one study, nearly 27% of pregnant women experienced an accidental fall [6], which is a rate comparable to the 30% rate of falls observed in individuals aged 65 yrs and older [7]. Falls that cause fractures and sprains can contribute to the fear of falling [8], while very serious falls can terminate maternal or fetal life [9,10].

Several researchers have studied the changes in postural control during pregnancy. Butler et al. reported that the center of pressure (COP) excursion in a pregnant group increased in length compared with a control group during quiet stance, and that the amount of weight gained was not significantly associated with the postural sway measures investigated [11]. Nagai et al. showed an increased area of body sway and length of anterior–posterior (A/P) body sway in a pregnant group compared with nonpregnant controls during quiet stance, and that high anxiety correlated with instability [12]. Oliveira et al. reported that pregnant women exhibited larger elliptical fits to COP trajectories as pregnancy progressed and higher COP frequency content along the A/P direction in the absence of visual inputs [13]. However, none of these studies addressed changes of postural control in response to external perturbations.

McCrory et al. investigated pregnant women's responses to A/P support surface translations [14]. Their main finding was that

* Corresponding author at: Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA. Tel.: +1 7346478249.
E-mail address: sienko@umich.edu (K.H. Sienko).

0966-6362/$ – see front matter
http://dx.doi.org/10.1016/j.gaitpost.2013.07.011

pregnant fallers, who reported at least one fall during pregnancy, had a truncated COP displacement immediately in response to the perturbation compared with pregnant nonfallers and controls.

Both the COP and center of gravity (COG) variables have been used individually to quantify postural stability in biomechanics studies. In terms of postural control during quiet standing, the COG and COP can be interpreted as the controlled and controlling variables, respectively [15–17], where the COP is proportional to the ankle torque [18]. COP and COG can also be measured simultaneously and the scalar difference between COP and COG (COP–COG) can be computed as a metric to characterize postural control. The COP–COG has been characterized in both the time and frequency domain. The most common metrics associated with the COP–COG variable are amplitude [18], standard deviation [17], root mean square [19], peak magnitude of displacement [20], latencies of initial and peak displacement [20], and frequency spectra [21]. COP–COG metrics have been applied, for example, to elderly stroke patients [19] and healthy elderly and young subjects [17], but have not yet been used to characterize balance in pregnant women.

In terms of mathematical modeling, the inverted pendulum, a one-link representation capturing a single degree of freedom, is the simplest mathematical model for describing bipedal postural control [22]. Simple one and two degree of freedom models have been used to study the effects of biofeedback on individuals with vestibular loss [23] and the risk of falling due to obesity [24]. However, to the best of our to our knowledge, these models have not been applied to pregnancy.

The specific goals of this study are (1) to investigate whether COP–COG can differentiate pregnant fallers from nonfallers; and (2) to use mathematical models to gain insights into the differences in postural control strategies between pregnant fallers and nonfallers.

2. Methods

The experimental data were obtained from a prior study of 15 women with a fall history during pregnancy (29.4 $\pm$ 4.7 yrs), 14 women without a fall history during pregnancy (30.6 $\pm$ 3.8 yrs), and 40 controls (26.5 $\pm$ 6.4 yrs) who were not pregnant and had a body mass index that matched the pre-pregnancy indices of the pregnant subjects [14]. The study had originally enrolled 41 pregnant women, however 12 subjects could not complete the study: four delivered pre-term, four had complications (preeclampsia, toxemia, fall with ankle sprain), three did not follow through, and one moved out of area. The average subject height was 165.8 $\pm$ 5.6 cm for the controls and 166.1 $\pm$ 6.6 cm for the pregnant women. Controls had a mass of 64.7 $\pm$ 8.8 kg, whereas the pregnant women had a mass of 73.9 $\pm$ 9.9 kg and 81.3 $\pm$ 11.1 kg in the second and third trimesters, respectively. Subjects in the pregnant and control groups were not matched based on the number of previous pregnancies. In the pregnant group, 27 women were primigravid; five stated it was their second pregnancy, and nine of the women said it was their third pregnancy. Thirty-three of the control women were nulligravid. Six controls reported that they were pregnant one time and one reported that she had been pregnant twice.

The pregnant subjects were tested twice. The first visit occurred in the middle of the second trimester. The average gestational age during the first data collection session was 20.9 $\pm$ 1.2 weeks. The second visit occurred at 35.8 $\pm$ 1.5 weeks. The controls participated in a single study visit.

Each participant gave informed consent prior to the start of the experimental procedures, and the study was conducted in accordance with the Helsinki Declaration and approved by the University of Pittsburgh Institutional Review Board. Participants were questioned as to their fall history during this pregnancy. Subjects were retrospectively classified as "pregnant fallers" if they fell at any point during their pregnancy. A fall was defined as a loss of balance such that any part of their body except the sole of the foot touched a support surface. Subject height and weight were obtained using a standard medical scale and stadiometer. Anthropometric data were collected according to the methods of Pavol et al. [25].

Translational surface perturbations in the anterior and posterior directions were generated using the Equitest (NeuroCom International, Inc., Clackamas, OR, USA) Motor Control Test (MCT). Three trials were performed at small, medium, and large perturbation magnitudes. The perturbation magnitude, i.e., the translation magnitude in inches, was determined through the manufacturer's formula $xh/72$, where h is the subject's height in inches, and x is 0.5 inches, 1.25 inches, and 2.25 inches for the small, medium, and large perturbations, respectively. All subjects were fitted with a chest and hip harness. The straps of the harness were only placed around the shoulders and upper thighs, thereby protecting the fetus (no subjects actually lost balance during testing). Subjects were instructed to stand on the platform with their feet hip-width apart and stare straight ahead. COP was directly measured and COG was estimated by the Equitest platform.

The peak COP–COG metric obtained was analyzed using a three-way ANOVA with Tukey's post hoc test (α = 0.05), where the subject group (controls (C), pregnant nonfallers (PNF), pregnant fallers (PF)), perturbation direction (backward, forward), and perturbation magnitude (small, medium, large) were designated as fixed factors. The experimental data from the second and third trimesters were averaged based on a one-way ANOVA (with trimester as the fixed factor) that showed that there was no significant difference in peak COP–COG between trimesters for any perturbation condition (p-values ranged from 0.12 to 0.99).

For the theoretical part of the study, a single-segmented mathematical model was considered first, but the goodness of fit for the COP data was worse when compared with the goodness of fit for a two-segmented representation; i.e., the single-segmented model was found to be inadequate for this application [26]. Thus, a two-segmented model was implemented to represent the dynamics of the body as shown in Fig. 1 along with the postural

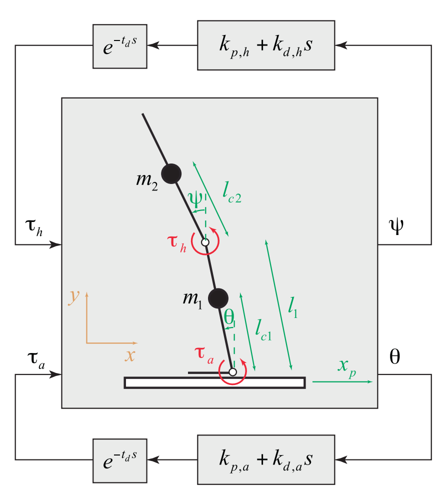

Fig. 1. The mathematical model employed in this study: a two-link inverted pendulum with lumped mass representation describes the dynamics of the body. x_p represents the platform position; l_1 is the first segment length, l_{c1}, and l_{c2} are the center of mass heights for segments 1 and 2, m_1 and m_2 are the segment masses, θ and ψ are the absolute ankle and hip joint ankles, and τ_a and τ_h are the ankle and hip joint torques. The feedback control loops around the ankle and hip joints represent the postural control model.