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A comparison of methods to determine center of mass during pregnancy

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ABSTRACT

Balance changes during pregnancy likely occur because of mass gains and mass distribution changes. However, to date there is no way of tracking balance through center of mass motion because no method is available to identify of the body center of mass throughout pregnancy. We compared methods for determining segment masses and torso center of mass location. The availability of a method for tracking these changes during pregnancy will make determining balance changes through center of mass motion an option for future pregnancy balance research. Thirty pregnant women from eight weeks gestation until birth were recruited for monthly anthropometric measurements, motion capture analysis of body segment locations, and force plate analysis of center of pressure during quiet standing and supine laying. From these measurements, we were able to compare regression, volume measurement, and weighted sum methods to calculate body center of mass throughout pregnancy. We found that mass changes around the trunk were most prevalent as expected, but mass changes throughout the body (especially the thighs) were also seen. Our findings also suggest that a series of anthropometric measurements first suggested by Pavol et al. (2002), in combination with quiet standing on a force plate, can be used to identify the needed components (segment masses and torso center of mass location in three dimensions) to calculate body center of mass changes during pregnancy. The results of this study will make tracking of center of mass motion a possibility for future pregnancy balance research.

1. Introduction

Pregnant women have been reported to fall at a rate similar to elderly (Dunning et al., 2010), with approximately 25% reporting at least one fall during the 40-week span of pregnancy (Dunning et al., 2003; Kuo et al., 2007), and some experiencing multiple falls. This prevalence is cause for concern, particularly given falls during pregnancy can lead to traumatic injury to the mother and harm to the fetus (Kuo et al., 2007). There is an increase in mass during pregnancy, mostly around the trunk (torso and pelvis), averaging about 15 kg (Ochsenbein-Kolble et al., 2007). Numerous studies indicate increased mass can cause balance changes (Catena et al., 2010; Cieslinska-Swider et al., 2017), and standing balance changes have been identified to occur during pregnancy (McCrory et al., 2010; Opala-Berdzik et al., 2010). Yet it is not well understood how the mass (amount and distribution) changes specific to pregnancy affect dynamic balance given there is no method to date that identifies the pregnant body center of mass (COM).

A validated model is needed to locate the COM from segment COMs in order to track dynamic balance during functional activities. Duel-energy X-ray absorptiometry scanning, a standard for identifying segment COMs, is not recommended with pregnant women because of low-dose radiation exposure. Magnetic resonance imaging is impractical for frequent use to track changes due to cost. A weighted sum of segment COMs is a practical and appropriate methodology for determining pregnancy related center of mass change, given it is both cost effective and non-invasive.

Using volume data and assumed densities from a sample of women throughout pregnancy, Jensen et al. reported a rate of change in mass distribution and moment of inertia of 16 body segments (Jensen et al., 1996). Rate of change for the lower trunk was the only significant change found through pregnancy. However, the investigators combined pelvis and lower torso, making the model difficult to use in future investigations of balance, given it is expected that the two segments would move with respect to each other during most functional activities.

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Pavol et al. developed a method to calculate participant specific segment masses and COMs in an obese population using a set of anthropometric measurements (Pavol et al., 2002). Their identification of segment COMs relative to joint centers and also finding separate pelvis, lower torso, and upper torso segments allows this method to be applied to motion capture data for locating the body COM during functional activities. As of yet, Pavol's (2002) method has not been validated in a pregnant population.

Alternatively, force plates can be used to identify the body COM location. The average location of the body center of gravity, a two dimensional projection of the COM in the transverse plane, will identify the location of the body COM (Opala-Berdzik et al., 2010). However, the use of a standing force plate analysis of center of pressure in this study could not identify vertical changes in the COM. Combining this with supine analysis of center of pressure spanning two force plates could be used to identify the vertical location of the COM and segment COMs (Park et al., 1999).

Using the three described methods above as a basis, we had two objectives in this study: (1) to compare the use of Jensen's (1996) data for segment mass determination (fit to linear regression specific to pregnant women) to Pavol's (2002) method (volume measurements and density assumptions) and (2) to determine pregnancy torso COM from Pavol's method (based on the weighted sum of five portions of a torso) vs. a force plate method for calculating the torso COM location. Additionally, this study will be the first to report a sample of changes in segment COMs throughout pregnancy. This information is important for measuring balance changes during pregnancy, given pregnant women are encouraged to be more physically active during pregnancy (Leavitt, 2008), but also told (ACOG, 2015; CDC, 2017) to reduce or avoid activities with an elevated risk of falling.

2. Materials and methods

Pregnant women (n = 30) were recruited from local obstetrical clinics for participation in this study (Table 1). Criteria to participate included being 18–40 years of age; not been categorized as high-risk pregnancy by a medical professional; and not having previously experienced recent lower extremity injury, vertigo, imbalances, or loss of consciousness. Participants were tested once a month until birth, beginning at eight weeks gestation.

IRB approved consent was obtained before each testing session. Each testing began with anthropometric measurements listed in Table 2 (Pavol et al., 2002). These measurements were collected using a digital scale (accurate to 0.1 kg), calipers (accurate to 1 mm), a fabric tape measure (accurate to 1 mm), and stadiometer (accurate to 1 mm). The measurements were recorded in a custom Excel (Microsoft Corp) table that would indicate if off by 5% of the accumulated average for the respective measurement to ensure inter-rater reliability. If the measure was outside ±5%, the value was rechecked via the same measurement procedure. All measurements were completed with the participant's shoes on to ensure comfort of our participants during standing, and shoe mass was accounted for in our analysis of body COM by adding the mass of the shoes into the reported foot mass (Catena et al., 2011). Fifty-four reflective markers were then adhered to landmarks on the participant (Fig. 1). Following this, participants maintained a standing position for 10 s on a force plate (Kistler 9260AA6) collecting center of pressure at 1000 Hz and motion captured using ten cameras (MotionAnalysis Corp.) collecting at 100 Hz. After standing, markers were removed from the posterior portion of the participant. The participant laid supine for 10 s on the back-board while data were collected (Fig. 1).

Table 1
Participant demographics at first testing.

	Mean	Standard deviation
Age	28.43	4.03
Mass (kg)	68.16	9.98
Height (cm)	168.54	6.65

Table 2
Anthropometric measurements made during testing based on Pavol et al. (2002).

Measurement	Description	Tool
BMI	Weight (kg)/(Height (m))^2	Calculation
Body height		Stadiometer
C7 height		Stadiometer
Acromion height (bilateral)		Stadiometer
Humeral head height (bilateral)		Stadiometer
Mid nipple height		Stadiometer
L3-4 height		Stadiometer
GT height L (bilateral)		Stadiometer
Head width	Measured at temple level	Calipers
Head depth	Measured at temple level	Calipers
Humeral head to humeral head width		Calipers
Torso depth at humeral head		Calipers
Torso width at nipple level		Calipers
Torso depth at nipple level		Calipers
Torso width nipple-L3-4	Half way between nipple level and L3-4 level	Calipers
Torso depth nipple-L3-4	Half way between nipple level and L3-4 level	Calipers
L3-4 Torso width		Calipers
L3-4 Torso depth		Calipers
Thigh length (bilateral)	Greater trochanter to tibial plateau	Calipers
Foot length (bilateral)	Toe to heel with shoes on	Calipers
Foot width (bilateral)	Base of the fifth metatarsal to medial to base of the first metatarsal	Calipers
Ankle width (bilateral)		Calipers
Head circumference	Measured from the center of the forehead	Tape measure
Neck circumference	Measured from the middle of the neck	Tape measure
Waist circumference	Measured at umbilicus height	Tape measure
Pelvis circumference	Measured at greater trochanter height	Tape measure
Upper arm circumference (bilateral)	Measured at mid point	Tape measure
Forearm circumference (bilateral)	Measured at widest point	Tape measure
Mid-thigh circumference (bilateral)	Measured at mid point	Tape measure
Shank length (bilateral)	Measured from tibial plateau to middle of lateral malleolus	Tape measure
Shank circumference (bilateral)	Measured at widest point	Tape measure
Lateral malleolus height (bilateral)	Measured from lateral malleolus to the ground	Tape measure

Motion capture data were filtered using a 6 Hz cutoff low-pass Butterworth filter. Joint centers were identified as the halfway point between medial and lateral markers at the elbows, wrists, knees, and ankles. The neck joint center was identified 40% of the distance from C7 marker to Sternal notch marker. The L3-4 joint center was identified as 50% of the distance from L3-4 in the

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