Applied Ergonomics 55 (2016) 173–182

Contents lists available at ScienceDirect

Applied Ergonomics

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

Estimation of inertial parameters of the lower trunk in pregnant Japanese women: A longitudinal comparative study and application to motion analysis

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A R T I C L E I N F O

Article history:
Received 30 July 2015
Received in revised form
10 February 2016
Accepted 10 February 2016
Available online 22 February 2016

Keywords:
Pregnant women
Body segment inertial parameters
Motion analysis

A B S T R A C T

We aimed to quantify the inertial parameters of the lower trunk segment in pregnant Japanese women and compare kinetic data during tasks calculated with parameters estimated in this study to data calculated with standard parameters. Eight pregnant women and seven nulliparous women participated. Twenty-four infrared reflective markers were attached to the lower trunk, and the standing position was captured by eight infrared cameras. The lower trunk was divided into parts, and inertial parameters were calculated. Pregnant women performed a movement task that involved standing from a chair, picking up plates, and walking forward after turning to the right. Kinetic analysis was performed using standard inertial parameters and the newly calculated parameters. There were more significant differences between methods in the kinetic data at the latter stages of pregnancy. The inertial parameters calculated in this study should be used to ensure the validity of biomechanical studies of pregnant Japanese women.

1. Introduction

The abdomen increases in mass and volume during pregnancy, causing changes in physical function. The center of mass (COM) location shifts and the alignment of the spine exhibits compensatory changes (Franklin and Conner-Kerr, 1998; Gaymer et al., 2009; Ostgaard et al., 1993). These changes in alignment differ between individuals (Gilleard et al., 2002) and can affect the musculoskeletal and postural control systems (Nagai et al., 2009; Ponnapula and Boberg, 2010), cause low back pain (Bastiaanssen et al., 2005; Cheng et al., 2009; Gutke et al., 2010; Lisi, 2006) and make it difficult for pregnant women to perform some activities of daily living (Garshasbi and Faghih Zadeh, 2005).

Previous biomechanical studies involving pregnant women have assessed changes in postural control during pregnancy. We reported that movement patterns of pregnant women during rising from a chair and walking forward were different from those of nulliparous women and varied with the number of days since conception (Sunaga et al., 2013). Difficulties performing a trunk flexion movement caused pregnant women to rise from a chair with insufficient forward displacement of their COM, meaning that they transitioned to walking and enhanced their forward propulsion after the transition to walking to compensate for insufficient forward displacement of the COM. Insufficient lower extremity lift and enhanced forward propulsion caused uncertain toe clearance and postural unsteadiness at the initiation of walking, increasing the risk of falling (Sunaga et al., 2013).

In the United States, accidental falls cause 10–25% of traumas during pregnancy (Connolly et al., 1997). Dunning et al. (2003) reported that the prevalence of falls in employed pregnant women was 26.6%, and that in non-employed pregnant women was 27.2%,

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http://dx.doi.org/10.1016/j.apergo.2016.02.010
0003-6870/

with the most common contributing factors to falls being slippery floors and carrying an object or a child. McCrory et al. (2011) demonstrated that pregnant women walked slower than non-pregnant women, and pregnant women who had fallen during pregnancy walked slower than pregnant women who had not fallen during pregnancy. Falls during pregnancy cause trauma for the mother and, at worst, intrauterine fetal death (Connolly et al., 1997; Dunning et al., 2003; El-Kady et al., 2004; Murao et al., 2000). Knowledge of postural control and movement patterns of pregnant women is necessary to develop safety guidelines to prevent falls.

Body segment inertial parameters (BSPs) are essential to understand human biomechanics. These include the ratio of segment mass to whole body mass, the distance of the segment COM from the edge of the body segment, and the radius of gyration of the segment. BSPs are required for kinetic analysis of movements, to calculate variables such as the COM location, joint moments, and joint powers. BSPs of Caucasian men (Chandler et al., 1975; Clauser et al., 1969; Dempster, 1955), young Japanese individuals (Ae et al., 1992), elderly Japanese individuals (Okada et al., 1996), and Japanese children (Yokoi et al., 1986) have been reported. Lee et al. (2009) reported the effects of BSP estimates on joint kinetics of the lower extremity during gait and highlighted the necessity of accurate BSP estimates. However, the available BSP estimates are not applicable to pregnant women, who have a distinctively different body shape to non-pregnant women (Yokoi et al., 2002). Furthermore, we believe that the BSPs of pregnant Japanese women will differ from those of pregnant Caucasian women, as, for example, the mean body mass gain of Japanese women during pregnancy is 9.8 kg (Tsukamoto et al., 2007), whereas that of Canadian women is 14.1 kg (Hui et al., 2006). A regression expression to estimate the BSPs of pregnant Canadian women has been presented (Jensen et al., 1996), but the BSPs of pregnant Japanese women have not been reported. As such, biomechanical studies have thus far used standard BSPs that are not applicable to pregnant women.

The aim of this study was to estimate the BSPs of pregnant Japanese women and quantify the changes in BSPs over time. These data will be useful for future motion analysis studies especially in analyzing motions in pregnant women. In addition, we compared BSPs between pregnant and nulliparous Japanese women. Jensen et al. (1996) reported that the lower trunk mass of pregnant Canadian women increased significantly in the second and third trimesters of pregnancy, but there were no significant changes in the mass of other body segments. Therefore, in this study, we focused only on the lower trunk segment.

Several methods have been used to estimate BSPs, including cadaver measurements (Chandler et al., 1975; Clauser et al., 1969; Dempster, 1955), mathematical modeling (Jensen, 1993; Jensen et al., 1996; Nikolva and Toshev, 2007), and X-ray scanning (Lee et al., 2009). Ideally, BSPs should be estimated in three dimensions, but methods involving radiation, such as X-ray scanning, are contraindicated for pregnant women. Ferrigno et al. (1994) calculated the volume of the trunk using a three-dimensional (3D) motion capture system, a method that was further validated by comparing inspired and expired lung volumes to volumes determined by spirometry (Cala et al., 1996). 3D motion capture has been widely used to analyze chest wall motion during breathing (Aliverti et al., 2001; Kenyon et al., 1997; Wang et al., 2009); however, to our knowledge, this method has not been previously used to estimate BSPs. In the present study, we used a 3D motion capture system, which has no undesirable effects on both the mother and fetus, to estimate BSPs of pregnant Japanese women. The estimated BSPs were used to perform kinetic analyses of pregnant women performing a movement task that involved rising from a chair, picking up square plates, turning to the right, and walking a few steps. In many cases, the motion of rising from a chair and walking also included turns to head toward a destination and perform some aimed motion. For these reasons, and in accordance with the increased risk of falling when carrying an object, we studied rising from a chair and turning while carrying an object, which seems to be routinely performed even during pregnancy.

2. Methods

2.1. Participants and measurements

Eight pregnant women (maternal group) with a mean age of 34.4 (SD 5.9) years, a mean body height of 160.3 (SD 4.1) cm, and a mean pre-pregnancy body mass of 55.4 (SD 6.6) kg volunteered for this study. Seven nulliparous women with a mean age of 29.3 (SD 2.4) years, a mean height of 156.5 (SD 5.6) cm, and a mean body mass of 52.4 (SD 7.6) kg also volunteered for this study and formed the control group. The maternal group was examined on the following three occasions: between the 16th and 18th weeks of gestation (Exam 1), between the 24th and 25th weeks of gestation (Exam 2), and between the 32nd and 33rd weeks of gestation (Exam 3), as per previous studies (Gilleard et al., 2008; Jang et al., 2008; Sunaga et al., 2013) and taking into consideration possible risks to the mother and fetus. The control group was examined on one occasion. Examinations of BSPs and motion were performed on the same day. The Ethics Committee of Saitama Prefectural University approved this study (Approval Number 24007), and the study was conducted in accordance with the Declaration of Helsinki. All participants provided their written, informed consent prior to enrollment.

2.2. Examination to estimate BSPs and motion analysis

Twenty-four infrared reflective markers were attached to the lower trunk and lower extremities of the subjects (Fig. 1), who were dressed in tight, non-reflective clothes. The lower edge of the 10th rib defined the top edge of the lower trunk segment, and the greater trochanter defined the bottom edge of the lower trunk segment. This segment division was based on previous studies involving Japanese individuals (Ae et al., 1992; Jensen, 1993; Nikolva and Toshev, 2007; Yokoi et al., 1986) and was chosen to enable comparisons across studies.

Standing posture was captured using eight infrared cameras (Vicon Motion Systems, Oxford, UK) while the subjects were standing comfortably and looking straight ahead. The coordinates of the markers were identified using a motion analysis software Vicon NEXUS 1.7.1. (Vicon Motion Systems, Oxford, UK). The center of the bottom edge of the posterior surface of the lower trunk segment was defined as the origin of the coordinate system, and the left-right, antero-posterior, and vertical axes of the lower trunk segment were defined as the x, y, and z axes, respectively. The coordinate system was orientated so that the right was positive and the left was negative.

For subjects in the maternal group, body mass, height of the uterine fundus, and abdominal girth were obtained at each examination using the most recent obstetric check-up record. Abdominal girth was measured at the level of the most projecting point around the navel. For subjects in the control group, body mass was measured on the day of the experiment.

For the maternal subjects, the markers were replaced after the examination of BSPs to enable measurement of the movement task. Thirty-five markers were attached to the subject at the following locations, according to the Plug-in-Gait Full Body Model (Vicon Motion Systems, 2010): right and left foreheads and back of the

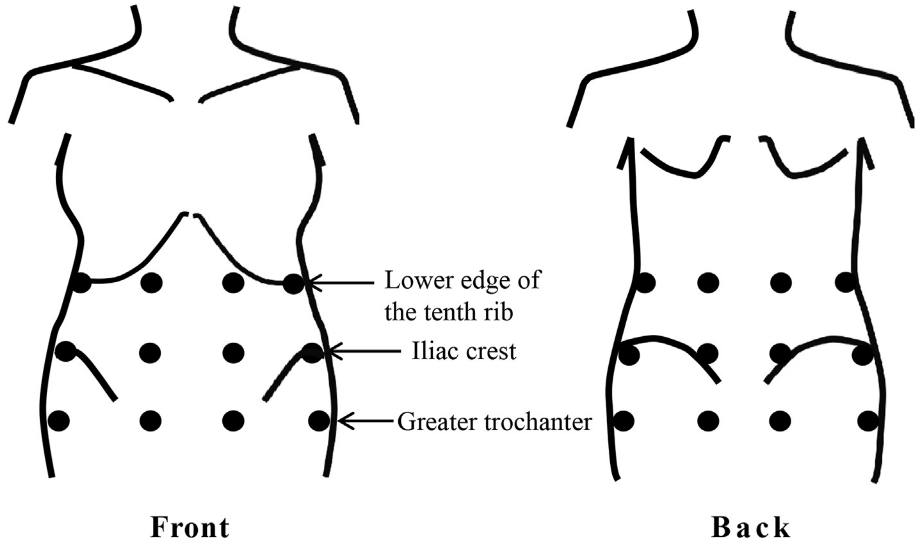


Fig. 1. Location of the markers used for the estimation of body segment inertial parameters.

heads, 7th cervical spinous process, 10th thoracic spinous process, suprasternal notch and xiphoid process of the sternum, the inferior edge of the right scapula, right and left acromia, elbows, thumb sides and digitus minimus sides of the wrists, bases of the second metacarpals, anterior superior iliac spines (ASISs), posterior superior iliac spines (PSISs), the center points of anteroposterior diameter exclude the patella located on the lateral surface of the knee joint space (knee markers), the points on the line connecting the knee markers and the points over the lateral 1/3 surface of the line from ASIS to the greater trochanter, the points on the fibula located on the upper 1/3 of the lower leg, the lateral malleoli, the heads of the first metatarsals, and the calcaneal tuberosities.

A table (height, 67 cm) was placed in front of a chair (height, 40 cm) without both backrest and armrests. Two legs of the table and chair are on the FP1 and FP3, FP2 and FP4, respectively (Fig. 2). The horizontal distance between the anterior edge of the seat of the chair and the near side of the top of the table was 25 cm, i.e., within reach of the subjects. The subjects rose from the chair and picked up two piled square plates (weight, 8.8 N; depth, 20 cm; width, 30 cm; height, 4 cm) from the table before stepping forward with the right foot and then turning 90° to the right and walking 3 m forwards at a self-selected speed. This task was performed three times at each exam. The location of the infrared markers was captured at 100 Hz using eight infrared cameras. Ground reaction force data were captured at 100 Hz by four force plates (Kistler, Winterthur, Switzerland) to define the instant when the plantar aspect of the foot lost contact with the floor during walking (Fig. 2). Force plates were set to 0 N with the table, chair and plates on.

2.3. Calculation of BSPs

The lower trunk was divided into six hexahedral parts, each consisting of six tetrahedrons. The six tetrahedrons were created by connecting each vertex of the hexahedrons, as described by

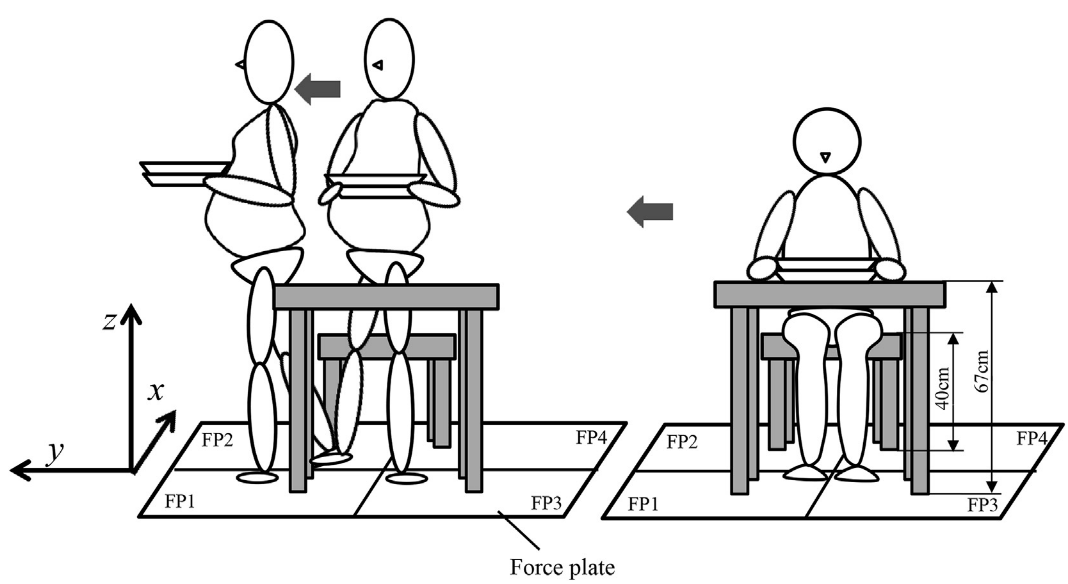


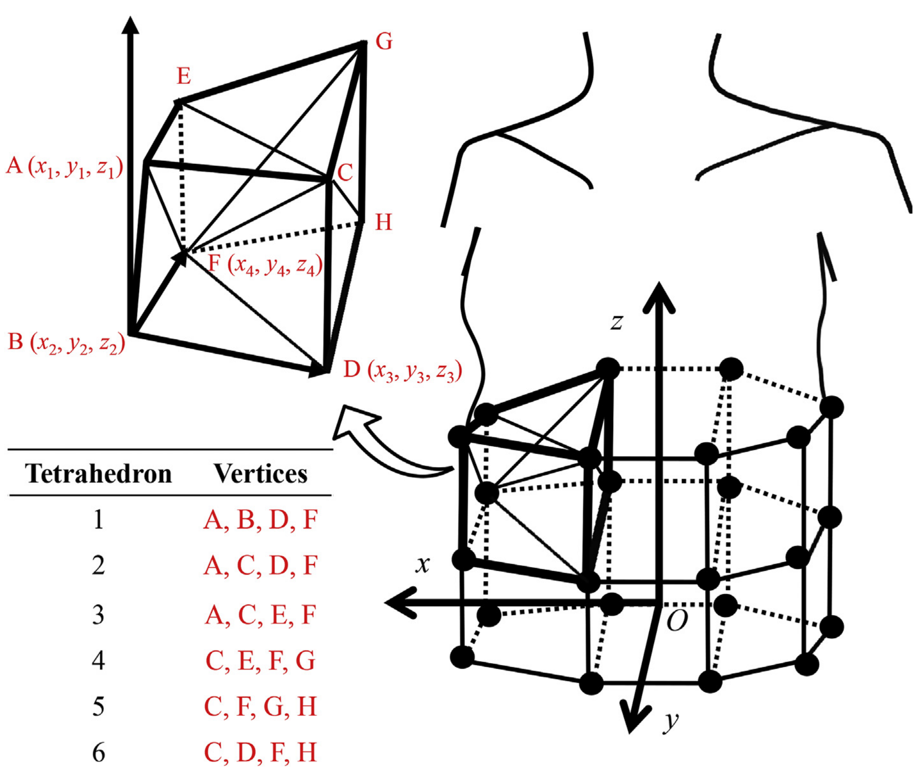
Fig. 2. Schematic showing the movement task performed. Subjects rose from a chair, picked up two piled square plates (weight, 8.8 N; depth, 20 cm; width, 30 cm; height, 4 cm), turned 90° to their right, and then walked forward while carrying the load. FP: Force plate.

Ferrigno et al. (1994) (Fig. 3). The volume of the tetrahedron 1 in Fig. 3 was calculated using the Eq. (A. 1) and the similar calculation method were applied to the volume of the other five tetrahedrons. The mass (M_j), COM coordinates (X_j, Y_j, Z_j), moment of inertia (I_{xj}, I_{yj}, I_{zj}), and radius of gyration (k_{xj}, k_{yj}, k_{zj}) of the lower trunk (j) were calculated using the parameters of the hexahedron obtained from the values of the individual tetrahedrons, according to Eqs. (A. 2)–(A. 5) in Appendix A. These formulas are in accordance with those reported by Yokoi et al. (1986). Eqs. (A. 3)–(A. 5) were modified to calculate the COM, moment of inertia, and radius of gyration in the x, y, and z directions. The lower trunk was assumed to be a rigid body segment with a uniform density of 1.037×10^3 kg/m^3 for the control group and Exam 1 of the maternal group and 1.030×10^3 kg/m^3 for Exams 2 and 3 of the maternal group (van Raaij et al., 1988). The coordinates of the segment COM were normalized to body height. The mass of the lower trunk segment was normalized to whole body mass. The Z coordinate of the COM location (Z_j) was calculated as the distance from the top of the segment and expressed relative to segment length. The moment of inertia was calculated as the principal of inertia when the lower trunk segment was gyrated about the left and right (x), anteroposterior (y), and vertical (z) at the COM coordinate. The radius of gyration was calculated when the lower trunk segment was gyrated about the left and right (x), anteroposterior (y), and vertical (z) at the COM coordinate and expressed relative to the lower trunk segment length. All calculations were performed in Microsoft Excel 2010 (Microsoft Japan, Tokyo, Japan).

2.4. Analysis of rising from a chair and carrying a load with a turn

For analysis of the movement task, the body was separated into 15 segments: the head, upper trunk, lower trunk, left and right upper arm, lower arms, hand, thigh, shank, and foot. For all segments apart from the lower trunk, the BSPs used were those of young nulliparous Japanese women reported by Ae et al. (1992). For the lower trunk segment, two different BSPs were used: those estimated in the subjects themselves using the data from the earlier part of the experiment (BSP1) and those of young nulliparous Japanese women reported by Ae et al. (1992) (BSP2). The lower trunk segment was defined as described above, and the moment of the lower trunk segment was calculated with the origin of the segment as the center of gyration. In the global coordinate system, the transverse, longitudinal, and vertical directions were defined as the x, y, and z axes, respectively, with right, forwards, and upward defined as positive. The local coordinate systems of the lower trunk segment are shown in Fig. 4. The center of the line connecting the right and left greater trochanters was defined as the origin. The vector crossing the origin and connecting the right and left greater trochanters was defined as the x axis. The vector crossing the origin and orthogonal to the vector connecting the center of the line between the right and left ASISs and the center of the line between the right and left PSISs and x axis was defined as the z axis. The vector crossing the origin and orthogonal to the x and z axes was defined as the y axis. The lower trunk moment was described as the inner moment when the lower trunk segment was gyrated about the x axis. The moment was defined as flexion and extension when the lower trunk segment was gyrated anteriorly and posteriorly, respectively. The moment of the lower trunk segment and the coordinates and velocity of the COM were calculated using Body Builder software (Vicon Motion Systems, Oxford, UK).

Initiation of motion in the movement task was defined as when the upper trunk flexion angle first increased while rising from a



Tetrahedron	Vertices
1	A, B, D, F
2	A, C, D, F
3	A, C, E, F
4	C, E, F, G
5	C, F, G, H
6	C, D, F, H

Fig. 3. The lower trunk segment model used to estimate inertial parameters. The lower trunk segment was divided into six hexahedral parts, each comprising six tetrahedrons. The six tetrahedrons were created by connecting each vertex of the hexahedrons. The mass (M_j), COM (X_j, Y_j, Z_j), inertial moment (I_{xj}, I_{yj}, I_{zj}), and radius of gyration (k_{xj}, k_{yj}, k_{zj}) of the lower trunk (j) were calculated for the lower trunk segment from the value of each tetrahedron using the mathematical Eqs. (A. 1)–(A. 4). n_j is the number of the hexahedrons in part j, d_j is the density of the part j, v_{ij} is the volume of the hexahedron ij and x_{ij}, y_{ij}, and z_{ij} are the coordinates of the COM of the hexahedron ij.

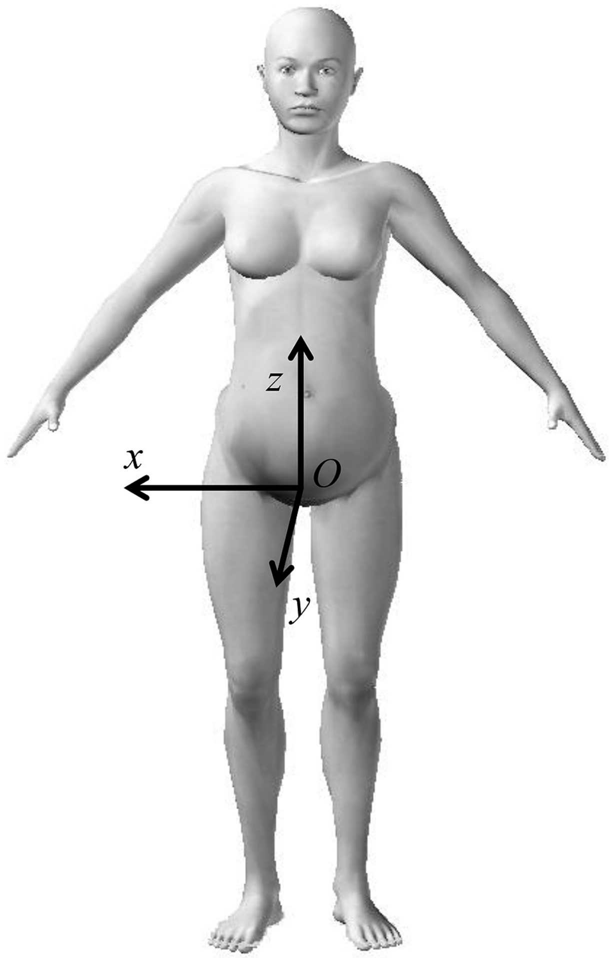


Fig. 4. The local coordinate system of the lower trunk segment. The center of the line connecting the right and left greater trochanters was defined as the origin. The vector crossing the origin and connecting the right and left greater trochanters was defined as the *x* axis. The vector crossing the origin and orthogonal to the vector connecting the center of the line between the right and left anterior superior iliac spines and the center of the line between the right and left posterior superior iliac spines and *x* axis was defined as the *z* axis. The vector crossing the origin and orthogonal to the *x* and *z* axes was defined as the *y* axis.

chair. Toe offs for the first swing leg and the stance leg were defined as when the vertical ground reaction force on the force plate was below 0 N because the force plates were set to 0 N with the table and chair on.

Three events during walking were identified according to Kerr et al. (2004): (1) first toe off of the first swing leg (1st swing-off); (2) first toe off of the first stance leg (stance-off); and (3) 2nd toe off of the first swing leg (2nd swing-off). The moment of the lower trunk segment and the location and velocity of the COM were calculated at initiation of motion and each of these events.

2.5. Statistical analyses

Statistical analyses were performed using SPSS Statistics 21 software (IBM Japan, Tokyo, Japan). One-way analysis of variance with a post-hoc Dunnett's test was performed to compare the body mass, height of the uterine fundus, abdominal girth, and BSPs between the groups, and repeated measures analysis was performed to compare within the maternal group. The body mass was compared between the control group and the four maternal groups (maternal before pregnancy, maternal Exam 1, maternal Exam 2, and maternal Exam 3). The height of the uterine fundus and abdominal girth were compared within three maternal groups (maternal Exam 1, maternal Exam 2, and maternal Exam 3). BSPs were compared between the groups and within the three maternal groups (maternal Exam 1, maternal Exam 2, and maternal Exam 3). A paired *t*-test was used to compare the lower trunk moment and the location and velocity of the COM calculated using BSP1 and BSP2. When the distribution of the values was not normally distributed, the Wilcoxon signed-rank test was used for this comparison. $P < 0.05$ was considered significant.

3. Results

3.1. BSPs of the lower trunk segment

Body mass, height of the uterine fundus, and abdominal girth are shown in Table 1. The body mass was significantly heavier at maternal Exam 3 than in the control group ($P = 0.028$). Body mass, height of the uterine fundus, and abdominal girth increased significantly within the maternal group (body mass: between before pregnancy and Exam 1, $P = 0.000$; before pregnancy and Exam 2, $P = 0.000$; before pregnancy and Exam 3, $P = 0.000$; maternal Exams 1 and 2, $P = 0.040$; maternal Exams 1 and 3, $P = 0.000$; maternal Exams 2 and 3, $P = 0.007$; height of the uterine fundus: between Exams 1and 2, $P = 0.043$; Exams 1 and 3, $P = 0.002$; Exams 2 and 3, $P = 0.022$; abdominal girth: between Exams 1 and 2, $P = 0.015$; Exams 1 and 3, $P = 0.004$).

The lower trunk segment length and absolute and relative masses are shown in Table 2. The lower trunk segment was significantly longer in the maternal group than in the control group (Exam 1, $P = 0.003$; Exam 2, $P = 0.001$; Exam 3, $P = 0.006$). The absolute and relative lower trunk segment masses were significantly greater in the maternal group at Exams 2 and 3 than in the control group (absolute mass: Exam 2, $P = 0.020$; Exam 3, $P = 0.006$; relative mass: Exam 2, $P = 0.003$; Exam 3, $P = 0.001$). In the maternal group, the absolute lower trunk segment mass at Exam 3 was significantly greater than at Exam 1 ($P = 0.026$).

The coordinates of the lower trunk segment COM are shown in Table 3. The segment COM was located more anteriorly (*Y* coordinate) in the maternal group at Exams 1, 2, and 3 than in the control group (Exam 1, $P = 0.030$; Exam 2, $P = 0.007$; Exam 3, $P = 0.003$), but there were no significant differences in the *X* and *Z* coordinates of the segment COM or in the relative position of the *Z* coordinate within the lower trunk segment between the groups and within the maternal group.

The moment of inertia of the lower trunk segment and the radius of gyration of the lower trunk segment expressed relative to segment length are shown in Table 4. The moment of inertia of the lower trunk segment about the *y* axis was significantly larger in the maternal group at Exam 3 than in the control group ($P = 0.035$). The radius of gyration about the *y* axis was significantly smaller in the maternal group than in the control group (Exam 1, $P = 0.001$; Exam 2, $P = 0.002$; Exam 3, $P = 0.036$).

3.2. Motion analysis

The moment of the lower trunk segment and the location and velocity of the COM at each event during the movement task are shown in Tables 5–7 when calculated with BSP1 and BSP2. There were more significant differences between BSP1 and BSP2 in the latter stages of pregnancy than in the early stage of pregnancy.

4. Discussion

In this study, BSPs of the lower trunk of pregnant Japanese

Table 1
Body mass, height of the uterine fundus, and abdominal girth.

Group	Round	Body mass [kg]	Height of the uterine fundus [cm]	Abdominal girth [cm]
Maternal	Before pregnancy	55.4 (6.6)	—	—
	Exam 1	58.2 (5.9)	16.3 (2.6)	79.8 (3.4)
	Exam 2	60.0 (6.2)	22.6 (2.3)	90.0 (2.9)†
	Exam 3	62.8 (6.6)†	29.0 (2.2)	93.0 (4.2)†
Control	—	52.4 (7.6)	—	—

Data are means (SD).

Exam 1: between the 16th and 18th weeks of gestation, Exam 2: between the 24th and 25th weeks of gestation, Exam 3: between the 32nd and 33rd weeks of gestation.

*: Significant difference within the maternal group at $P < 0.05$.

†: Significant difference from the control group at $P < 0.05$.

Table 2
Lower trunk segment length and absolute and relative masses.2

Group	Round	Segment length [m]	Segment mass [kg]	Ratio of segment mass to whole body mass [%]
Maternal	Exam 1	0.198 (0.0048)†	11.5 (5.6)	16.3 (2.6)
	Exam 2	0.195 (0.0187)†	13.6 (3.0)†	22.6 (2.3)†
	Exam 3	0.193 (0.0169)†	14.7 (2.0)†	29.0 (2.2)†
Control	—	0.160 (0.017)	9.5 (2.8)	15.9 (1.9)

Data are means (SD).

Exam 1: between the 16th and 18th weeks of gestation, Exam 2: between the 24th and 25th weeks of gestation, Exam 3: between the 32nd and 33rd weeks of gestation.

*: Significant difference within the maternal group at $P < 0.05$.

†: Significant difference from the control group at $P < 0.05$.

Table 3
Location of the lower trunk segment COM.

Group	Round	COM location [% body height]			Distance of COM from the top of the segment [% segment length]
		X	*Y*	*Z*	
Maternal	Exam 1	0.062 (0.54)	9.614 (1.30)[a]	6.237 (0.49)	50.4 (3.5)
	Exam 2	−0.377 (0.95)	9.841 (0.80)[a]	5.733 (0.97)	54.0 (4.4)
	Exam 3	0.165 (1.05)	10.034 (0.56)[a]	5.480 (0.77)	54.3 (7.1)
Control	–	−1.019 (2.29)	8.266 (0.25)	5.093 (0.50)	49.9 (4.4)

Data are means (SD).
Exam 1: between the 16th and 18th weeks of gestation, Exam 2: between the 24th and 25th weeks of gestation, Exam 3: between the 32nd and 33rd weeks of gestation.
X coordinate: positive values indicate right and negative values indicate left of the origin of the coordinate system.
[a] Significant difference from the control group at $P < 0.05$.

Table 4
Moment of inertia and radius of gyration of the lower trunk segment.

Group	Round	Moment of inertia [kg m^2]			Radius of gyration [% segment length]		
		I_x	I_y	I_z	k_x	k_y	k_z
Maternal	Exam 1	0.0338 (0.0077)	0.0772 (0.0120)	0.0611 (0.0114)	27.4 (3.9)	41.3 (1.8)[a]	36.7 (3.8)
	Exam 2	0.0400 (0.0298)	0.1004 (0.0337)	0.0812 (0.0384)	25.8 (6.4)	42.7 (2.5)[a]	37.9 (5.5)
	Exam 3	0.0379 (0.0126)	0.1114[a] (0.0327)	0.0765 (0.0219)	26.0 (1.7)	44.9 (4.0)[a]	37.3 (4.2)
Control	–	0.0150 (0.0041)	0.0635 (0.0307)	0.0494 (0.0281)	25.3 (3.2)	50.2 (4.1)	43.5 (4.1)

Data are means (SD).
Exam 1: between the 16th and 18th weeks of gestation, Exam 2: between the 24th and 25th weeks of gestation, Exam 3: between the 32nd and 33rd weeks of gestation.
[a] Significant difference from the control group at $P < 0.05$.

Table 5
The lower trunk moment at specified events during the movement calculated using BSP1 and BSP2.

Event	Lower trunk moment	Round	BSP1	BSP2	*P*
Rising from a chair	Peak of extension	Exam 1	0.47 (0.052)	0.50 (0.093)	0.422
		Exam 2	0.46 (0.087)	0.44 (0.092)	**0.041**
		Exam 3	0.50 (0.016)	0.44 (0.064)	**0.005**
1st swing-off	Extension	Exam 1	0.52 (0.128)	0.58 (0.125)	0.589
		Exam 2	0.57 (0.050)	0.54 (0.055)	**0.009**
		Exam 3	0.55 (0.522–0.608)	0.51 (0.485–0.567)	**0.018**
	Rotation	Exam 1	0.15 (0.037)	0.14 (0.033)	0.437
		Exam 2	0.19 (0.035)	0.18 (0.037)	0.440
		Exam 3	0.16 (0.138–0.176)	0.17 (0.140–0.175)	0.128
Stance-off	Extension	Exam 1	0.56 (0.111)	0.62 (0.105)	0.365
		Exam 2	0.55 (0.048)	0.53 (0.051)	**0.002**
		Exam 3	0.58 (0.047)	0.55 (0.046)	**0.001**
2nd swing-off	Extension	Exam 1	0.68 (0.066)	0.72 (0.117)	0.387
		Exam 2	0.63 (0.084)	0.61 (0.090)	0.128
		Exam 3	0.65 (0.090)	0.63 (0.082)	**0.002**

Data are means (SD) or medians (interquartile range).
BSP1: parameters of the lower trunk segment of maternal subjects calculated in this study.
BSP2: parameters of the lower trunk segment of young nulliparous Japanese women reported by Ae et al.
Bold text indicates significant P values.

Table 6
The COM location at focused events during the movement calculated using BSP1 and BSP2.

Event		Round	BSP1	BSP2	*P*
1st swing-off	*x*	Exam 1	−0.125 (0.012)	−0.127 (0.013)	**0.001**
		Exam 2	−0.136 (0.023)	−0.133 (0.021)	0.082
		Exam 3	−0.134 (0.028)	−0.124 (0.025)	**0.000**
	y	Exam 1	−0.014 (0.022)	−0.014 (0.022)	0.379
		Exam 2	−0.034 (−0.039 to −0.016)	−0.036 (−0.038 to −0.027)	0.889
		Exam 3	−0.027 (0.025)	−0.024 (0.023)	**0.004**
	z	Exam 1	0.865 (0.019)	0.871 (0.018)	0.369
		Exam 2	0.911 (0.031)	0.882 (0.024)	**0.000**
		Exam 3	0.980 (0.027)	0.890 (0.020)	**0.000**
Stance-off	*x*	Exam 1	0.00341 (0.016)	0.00411 (0.017)	0.143
		Exam 2	−0.00039 (0.016)	0.00081 (0.018)	0.799
		Exam 3	−0.00196 (0.010)	−0.00301 (0.009)	0.220
	y	Exam 1	0.322 (0.065)	0.332 (0.069)	**0.005**
		Exam 2	0.326 (0.082)	0.316 (0.045)	0.621
		Exam 3	0.345 (0.071)	0.312 (0.059)	**0.002**
	z	Exam 1	0.870 (0.020)	0.891 (0.020)	**0.000**
		Exam 2	0.922 (0.031)	0.892 (0.023)	**0.000**
		Exam 3	0.990 (0.028)	0.899 (0.023)	**0.000**
2nd swing-off	*x*	Exam 1	−0.00036 (0.015)	−0.00075 (0.015)	0.101
		Exam 2	0.00443 (0.024)	0.00526 (0.016)	0.829
		Exam 3	0.01196 (0.005–0.015)	0.01071 (0.005–0.015)	0.398
	y	Exam 1	0.812 (0.129)	0.838 (0.134)	**0.001**
		Exam 2	0.806 (0.129)	0.795 (0.115)	0.701
		Exam 3	0.904 (0.144)	0.817 (0.124)	**0.000**
	z	Exam 1	0.851 (0.017)	0.871 (0.018)	**0.000**
		Exam 2	0.902 (0.032)	0.876 (0.024)	**0.001**
		Exam 3	0.970 (0.023)	0.877 (0.021)	**0.000**

Data are means (SD) or medians (interquartile range).
BSP1: parameters of the lower trunk segment of maternal subjects calculated in this study.
BSP2: parameters of the lower trunk segment of young nulliparous Japanese women reported by Ae et al.
Bold text indicates significant P values.

Table 7
The COM velocity at focused events during the movement calculated using BSP1 and BSP2.

Event		Round	BSP1	BSP2	*P*
1st swing-off	*x*	Exam 1	0.08 (0.032)	0.07 (0.041)	0.487
		Exam 2	0.07 (0.034)	0.07 (0.033)	0.172
		Exam 3	0.07 (0.034)	0.08 (0.058)	0.845
	y	Exam 1	0.08 (0.045)	0.07 (0.051)	0.467
		Exam 2	0.05 (0.050)	0.07 (0.080)	0.462
		Exam 3	0.06 (0.081)	0.07 (0.100)	0.568
	z	Exam 1	0.03 (0.025)	0.03 (0.025)	0.940
		Exam 2	0.05 (0.024)	0.04 (0.025)	**0.043**
		Exam 3	0.03 (0.031–0.049)	0.03 (0.028–0.068)	0.866
Stance-off	*x*	Exam 1	0.15 (0.020)	0.15 (0.025)	0.257
		Exam 2	0.15 (0.047)	0.15 (0.041)	0.077
		Exam 3	0.16 (0.133–0.185)	0.16 (0.126–0.168)	**0.028**
	y	Exam 1	0.58 (0.572–0.699)	0.61 (0.587–0.671)	0.345
		Exam 2	0.64 (0.124)	0.66 (0.191)	0.059
		Exam 3	0.81 (0.654–0.842)	0.75 (0.596–0.804)	**0.028**
	z	Exam 1	0.03 (0.020)	0.04 (0.030)	0.357
		Exam 2	0.04 (0.017)	0.03 (0.021)	0.143
		Exam 3	0.04 (0.035)	0.07 (0.095)	0.443
2nd swing-off	*x*	Exam 1	−0.11 (0.040)	−0.12 (0.041)	0.390
		Exam 2	−0.12 (0.067)	−0.10 (0.049)	0.828
		Exam 3	−0.08 (0.033)	−0.08 (0.034)	0.414
	y	Exam 1	0.93 (0.118)	1.00 (0.156)	0.377
		Exam 2	0.94 (0.266)	0.98 (0.245)	0.758
		Exam 3	1.02 (0.257)	1.05 (0.189)	0.093
	z	Exam 1	0.08 (0.060–0.126)	0.12 (0.064–0.128)	0.345
		Exam 2	0.07 (0.054–0.089)	0.06 (0.053–0.084)	0.161
		Exam 3	0.08 (0.039)	0.08 (0.039)	0.426

Data are means (SD) or medians (interquartile range).
BSP1: parameters of the lower trunk segment of maternal subjects calculated in this study.
BSP2: parameters of the lower trunk segment of young nulliparous Japanese women reported by Ae et al.
Bold text indicates significant P values.

women were quantified using a 3D motion capture system at three different times during pregnancy and compared with those of nulliparous women. The lower trunk segment length was significantly longer in the control group than in the maternal group because of individual variability in physical constitution between subjects in this study. Moreover, the lower trunk segment length decreased as pregnancy progressed, although there was no significant difference. This result could have been due to increasing spinal curvature. The absolute and relative lower trunk segment masses were significantly greater in the maternal group at Exams 2 and 3 than in the control group, although there was no significant difference at Exam 1. This result represents the lower trunk segment mass is not affected by uterine increase at the period of the Exam 1. Additionally, the absolute and relative masses of the lower trunk segment increased as pregnancy progressed. Jensen et al. (1996) reported that the lower trunk segment mass of pregnant Canadian women increased from 21.6 kg to 28.4 kg between the 2nd and 9th months of gestation, i.e. by 0.29 kg per week during pregnancy. In the present study, the lower trunk segment mass of pregnant Japanese women increased from 11.5 kg to 14.7 kg between 16th and 33rd weeks of gestation, i.e., by 0.19 kg per week. This corresponds to an increase of 27.8%, compared to an increase of 25.2% between the 16th and 33rd weeks of gestation in Canadian women, as estimated from the linear regression in Jensen et al. (1996). This difference may be due to differences in the physical constitution, timing of the weight gain of the two study populations.

The relative mass of the lower trunk segment in nulliparous and pregnant women at Exam 1 in this study was smaller than that reported by Ae et al. for young Japanese women (1992). This may be due to differences in the measurement method and/or the method of division of the lower trunk segment. The relative mass of the lower trunk segment in pregnant women at Exams 2 and 3 was greater than that in the young female Japanese individuals reported by Ae et al. (1992). This result indicates that changes in maternal morphology were captured using the methods used in this study.

The *Y* coordinate of the lower trunk segment COM was significantly more anterior in the maternal group than in the control group, but there were no significant differences in the *X* and *Z* coordinates of the lower trunk segment COM or the relative location of the *Z* coordinate within the lower trunk segment between maternal and control groups. The anterior shift of the lower trunk segment COM in the maternal group occurred because of the anterior shift of the heavy part of the abdomen.

The moment of inertia of the lower trunk segment I_y was significantly larger in pregnant women at Exam 3 than in nulliparous women. Jensen et al. (1996) reported that the moment of inertia of the lower trunk segment increased at a rate of 0.00679, 0.00474, and 0.00612 kg m^2 per week throughout pregnancy for I_x, I_y, and I_z, respectively, and these rates of change were greater than those for all other segments. The result in this study indicated that the moment of inertia was affected by the change of body mass during pregnancy. Additionally, the variables related to moment of inertia, such as the COM location and the mass of the lower trunk segment, changed due to high inter-subject variability in the timing of the appearance of the abdominal protrusion and in physical constitution.

When expressed relative to the segment length, the radius of gyration was smaller in pregnant women at Exam 1 to 3 than in nulliparous women, and this was due to the longer segment length and larger segment mass of the maternal group.

The effect of pregnancy on BSPs should be considered in biomechanical analyses of pregnant women. The radius of gyration of the lower trunk segment, which was significantly different between pregnant women at Exam 1 to 3 and nulliparous women, is generally incorporated in motion analysis software. The ratio of the lower trunk segment mass to whole body mass and the COM location of the lower trunk segment are also generally incorporated in motion analysis software. In this study, these variables were incorporated into the analysis of a movement in which subjects rose from a chair and carried an object while walking. The results showed that these variables affected biomechanical parameters. Possible risk factors for falling during pregnancy, there are precious few studies which have been identified in detail, may be investigated by using BSPs produced by motion analysis assessment of pregnant women. As detailed in Section 1, the increases in mass and volume of the abdomen that occurs during pregnancy cause changes in physical function, and the validity and reliability of biomechanical analysis of pregnant women would be improved by the use of appropriate BSPs.

Physical constitution varies not only with pregnancy, but also with other variables, such as stage of pregnancy, race, and age, therefore biomechanical analyses should be performed based on valid BSPs. We believe that the method used in the present study to determine BSPs is useful, since it uses the same equipment that is used to perform motion analysis, and motion analysis can therefore be performed in the same session if the infrared makers are relocated. The small number of subjects and the inter-individual variability in physical constitution are the main limitations of this study. However, the changes of BSPs affect the biomechanics of motion, so that the data measured at each period of pregnancy are important basic data. Additionally, it is recommended that BSPs be applied as specific data to individuals, if possible.

5. Conclusions

The absolute and relative masses, the COM location, the moment of inertia, and the radius of gyration of the lower trunk segment of pregnant Japanese women were estimated using a novel approach based on a 3D motion capture system. The moment of inertia changed as pregnancy progressed. Therefore, different BSPs should be used in biomechanical analyses of pregnant women according to the stage of pregnancy and each pregnant subject. Further research is required to validate these results by using the estimated BSPs proposed in this study in the motion analysis of pregnant women.

Acknowledgments

This study was supported in part by Grants-in-Aid for Scientific Research awarded by the Japan Society for the Promotion of Science (Grant Number 24792502 and 15K11664).

Appendix A

The volume of the tetrahedron 1 in Fig. 3 was calculated using the Eq. (A. 1) and the similar calculation were applied to the volume of the other five tetrahedrons. The sum of the volume of the six tetrahedrons was used for calculate the Eqs. (A. 2)–(A. 5).

n_j is the number of the hexahedrons in part j, d_j is the density of part j, v_{ij} is the volume of the hexahedron ij, and x_{ij}, y_{ij}, and z_{ij} are the coordinates of the COM of hexahedron ij.

Volume of the tetrahedron

$$V = \frac{\overrightarrow{BA}\left(\overrightarrow{BD}\,\overrightarrow{BF}\right)}{6}$$

$$\begin{aligned}\overrightarrow{BA}\left(\overrightarrow{BD}\,\overrightarrow{BF}\right) = {} & (x1-x2)[(y3-y2)(z4-z2)-(z3-z2)(y4-y2)] \\ & +(y1-y2)[(z3-z2)(x4-x2)-(x3-x2)(z4-z2)] \\ & +(z1-z2)[(x3-x2)(y4-y2)-(y3-y2)(x4-x2)]\end{aligned} \tag{A. 1}$$

Mass of the lower trunk segment

$$M_j = \sum\nolimits_i^{n_j} (d_j v_{ij}) \tag{A. 2}$$

COM coordinate of the lower trunk segment

$$X_j = \sum\nolimits_i^{nj} (d_j v_{ij} x_{ij}) / M_j \tag{A. 3}$$

(The similar calculation method were applied to Y_j, Z_j)
Inertia moment of the lower trunk segment

$$I_{xj} = \sum\nolimits_i^{n_j} \left[d_j v_{ij} \left\{ \left(y_{ij} - Y_j \right)^2 + \left(z_{ij} - Zj \right)^2 \right\} \right] \tag{A. 4}$$

(The similar calculation method were applied to I_{yj}, I_{zj})
Radius of gyration of the lower trunk segment

$$kxj = \left(I_{xj} / M_j \right)^{1/2} \tag{A. 5}$$

(The similar calculation method were applied to k_{yj}, k_{zj})

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