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Original Research

Validity of the top-down approach of inverse dynamic analysis in fast and large rotational trunk movements

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Abstract

This study investigated the validity of the top-down approach of inverse dynamic analysis in fast and large rotational movements of the trunk about three orthogonal axes of the pelvis for nine male collegiate students. The maximum angles of the upper trunk relative to the pelvis were approximately 47°, 49°, 32°, and 55° for lateral bending, flexion, extension and axial rotation, respectively, with maximum angular velocities of 209°/s, 201°/s, 145°/s, and 288°/s, respectively. The pelvic moments about the axes during the movements were determined using the top-down and bottom-up approaches of inverse dynamics and compared between the two approaches. Three body segment inertial parameter sets were estimated using anthropometric data sets (Ae et al., Biomechanism 11, 1992; De Leva, J Biomech, 1996; Dumas et al., J Biomech, 2007). The root-mean-square errors of the moments and the absolute errors of the peaks of the moments were generally smaller than 10 Nm. The results suggest that the pelvic moment in motions involving fast and large trunk movements can be determined with a certain level of validity using the top-down approach in which the trunk is modeled as two or three rigid-link segments.
**Introduction**

The moments acting on the L5/S1 joint or the pelvis have been determined to assess the risk for lower back injuries and to elucidate the basic mechanism of motions in various movements, such as manual material handling tasks (e.g., Larivière et al., 2002), walking (Callaghan et al., 1999) and tennis strokes (Akutagawa & Kojima, 2004; Iino & Kojima, 2001; Kawasaki et al., 2003). Inverse dynamics has been generally used to determine these moments. Two approaches are available for the determination: the top-down and bottom-up approaches (Kingma et al., 1996; Plamondon et al., 1996; Larivière & Gagnon, 1998; Larivière & Gagnon, 1999a). The former approach uses kinematic data of the upper body and, if necessary, external force data, whereas the latter uses kinematic data of the lower limbs and ground reaction force data. Although the latter approach may produce more accurate results than the former (Desjardins et al., 1998), the use of force plates for acquiring force data may constrain the motion of the feet and hinder the natural movements being examined. Furthermore, it may not be possible to use the plates in some situations, such as during sport competitions. The top-down approach, however, is applicable even in these situations.

The spine has considerable rotational ranges of motion about its three anatomical axes. Total maximum ranges of motion for the thoracic and lumbar region with respect to the pelvis are normally 105°, 60°, 40°, and 40° for flexion, extension, lateral bending, and axial rotation, respectively (Kapandji, 2008). Large spine movements have been observed in sport motions (Lindsay & Horton, 2008; Iino & Kojima, 2001; Stodden et al., 2001). Lindsay and Horton (2008) reported that the ranges of motions of the spine of professional golfers in hitting a driver were 40.5° for flexion-extension, 30.4° for lateral bending and 84.0° for axial rotation. In tennis forehands, the shoulders (i.e., a line connecting both shoulder joint centers) rotated
by $37^\circ$ relative to the pelvis in a horizontal plane during the forward swing (Iino & Kojima, 2001). Stodden et al. (2001) reported that the upper torso axially rotated by $68^\circ$ relative to the pelvis in baseball pitching. Hence, the assumption that trunk segments are rigid, which is commonly made in inverse dynamics, may not be valid for these motions.

Several researchers have investigated the sensitivities of the L5/S1 joint or pelvic moment determined using inverse dynamics to different types of errors (Desjardins et al., 1998; Larivière & Gagnon, 1999b; Riemer et al., 2008). However, a sensitivity analysis does not seem suitable for assessing the validity of the inverse dynamic analysis of the upper body for motions involving large spine movements. This is because, in an inverse dynamic model, it is difficult to estimate realistic error magnitudes of the input variables associated with the rigid body assumption made for the trunk.

The validity of inverse dynamic analysis of the upper body has also been investigated through the comparison of the L5/S1 or thorax–pelvis joint moments determined using the top-down and bottom-up approaches in lifting tasks (Kingma et al., 1996; Plamondon et al., 1996; Larivière & Gagnon, 1998; Larivière & Gagnon, 1999a) and balance recovery movements (Robert et al., 2007). These studies reported that the differences in the peaks of the moments between the two approaches were generally smaller than 10–20 Nm and the root-mean-square (RMS) differences in the moments were smaller than 10 Nm, suggesting that the inverse dynamic calculation is valid for producing at least a general profile of the moment patterns. However, the ranges of motion and movement speeds were not necessarily documented well in these studies and it is unclear whether the resulting findings are applicable to fast and large rotational trunk movements, such as in the sport motions cited above. Hence, it would be useful to investigate the validity of the top-down approach of
inverse dynamic calculations in fast and large rotational trunk movements about the three anatomical axes.

Body segment inertial parameters (BSP) have been estimated using different anthropometric data sets (Ae et al., 1992; De Leva, 1996; Dumas et al., 2007). The numbers of the segments and the boundary definitions differ among the data sets and these differences may affect the validity of inverse dynamics.

The purpose of this study was to investigate the validity of the top-down approach of inverse dynamic analysis in fast and large rotational movements of the trunk about the three orthogonal pelvic axes. We used the regression methods provided by previous studies (Ae et al. 1992; De Leva, 1996; Dumas et al., 2007) to estimate the BSP because the methods are less cumbersome (Larivièrè & Gagnon, 1999a) and can be adopted in more diverse situations than other methods such as geometric methods (Hanavan, 1964; Yeadon, 1990).

Methods

Participants

Nine healthy male Japanese college students participated in this study. Their mean (range) age, height, body mass and body mass index (BMI) were 21.2 (19–25) years, 1.72 (1.61–1.82) m, 61.8 (50.4–74.6) kg and 20.7 (18.3–23.6) kg/m², respectively. They provided written informed consent before participating in the study. The experimental procedure of the study was approved by the local ethical committee.

Experimental procedure

The participants wore tight swim suits after warming-up. A total of 59 retroreflective
Markers with a diameter of 16 mm were attached to the body surfaces of each participant (Figure 1). For the trunk part, four markers were attached to the skin surfaces of the suprasternal notch (SUP), the xiphoid process (XIP), the midpoint of the lowest ends of the right and left ribs (RIB), and the navel (NAB). Markers were also attached to four points on the posterior midline at the same heights as the above-mentioned four markers when the participants were standing upright; these markers are denoted by PSUP, PXIP, PRIB, and PNAB, respectively. A marker was attached to the seventh cervical vertebra (C7). Markers were also attached to the head vertex; the left and right tragi; the acromions; the inferior angles and superior angles of both scapulae; the right and left anterior superior iliac spines (RASIS, LASIS); the midpoint of both posterior superior iliac spines (MPSIS); the lateral and medial epicondyles of both humerals; the ulnar and radial styloid processes of both wrists; the metacarpal head IIs and Vs of both hands; a lateral point of each upper arm, forearm, thigh, and shank; both great trochanters; the lateral and medial epicondyles of both femurs; the lateral and medial malleoli of both ankles; both heels; both tiptoes; and the metatarsal head IIs and Vs of both feet.

The participants were asked to perform three tasks of trunk lateral bending, flexion–extension, and axial rotation as quickly as possible while making their movement ranges as large as possible with each foot on a different force plate (9281B, Kistler). The lateral bending task was a sequential motion consisting of bending of the trunk to one side from an upright position followed by bending to the other side through the position and returning to the position. The flexion–extension task was a sequential motion consisting of a trunk flexion from the upright position, followed by a trunk extension through the position, and returning to the position. The axial rotation task was a sequential motion consisting of
an axial rotation of the trunk to one side from the upright position, followed by the axial rotation to the other side through the position, and returning to the position.

A three-dimensional (3D) motion-capture system with eight MXf20 cameras (Vicon Motion Systems, Oxford, UK) was used to collect 3D coordinate data of the markers at 200Hz. The force plate data from the two force plates were recorded using two charge amplifiers (9865C, Kistler, Switzerland) and an A/D converter at 1000 Hz, and were electronically synchronized with the motion-capture recording.

Data smoothing

The 3D coordinate data of the markers were smoothed using a zero-phase lag Butterworth low pass digital filter with a cutoff frequency of 5Hz.

Determination of the limb joint centers

The joint centers of the right and left shoulder joints (RSHO, LSHO) and both hip joints (HIPs) were estimated using a functional method (Gamage & Lasenby, 2002) adjusted by Halvorsen (2003). For this purpose, the participants were asked to perform a sequence of movements of flexion, extension, and abduction of each joint, and circumduction of the limb at the joint. The elbow, wrist, knee, and ankle joint centers were determined as the midpoints of the relevant lateral and medial markers.

3D link-segment models of the whole body

Three BSP sets of the whole body were estimated using the three anthropometric data sets: (1) Ae et al. (1992); (2) De Leva (1996), who adjusted the data of Zatsiorsky and
Seluyanov (1983); (3) Dumas et al. (2007), who adjusted the data of McConville et al. (1980) (Table 1). These data sets will be referred to as AE, DE, and DU, respectively. In the data of Ae et al. (1992), the trunk is divided into two segments that are separated by the transverse section passing through the lowest ends of both ribs. In the data of De Leva (1996), the trunk is divided into three segments that are separated by the transverse sections passing through the xiphoid process and the navel. In the data of Dumas et al. (2007), the trunk is divided into two segments separated by the transverse section passing through the iliocristale.

The right-handed segment coordinate systems of all segments were determined using the method of Veldpaus et al. (1988), which determined the direction cosine matrix of each segment from the 3D coordinates of three or more non-collinear markers attached to the segment at each time instant. The coordinate systems of the limb segments were determined using the relevant lateral and medial markers and joint centers. The definitions of the coordinate systems of the trunk segments and the markers used for the definitions are shown in Table 2. The endpoint locations of the trunk segments in the antero-posterior direction are not provided in the data of Ae et al. (1992) and De Leva (1996). Larivièrre and Gagnon (1999a) reported that a more posterior location of the center of mass (COM) of the trunk, based on Plagenhoef (1971) after Parks (1959), provided smaller differences between the L5/S1 joint moments determined using the top-down and bottom-up approaches than the COM at the 50% depth of the trunk. Hence, the endpoints of the trunk segments were assumed to be located at the 40% width (i.e., distance between the anterior and posterior markers), anterior from the posterior markers in the BSP sets of AE and DE according to Plagenhoef (1971).
Determination of the pelvic moment using top-down and bottom-up approaches

The pelvic moment defined as the moment acting on the pelvis about the midpoint of the hip joint centers from the lower limbs was determined using the top-down and bottom-up inverse dynamic approaches (Hof, 1992) for the AE, DE, and DU BSP sets. The angular velocity of each segment of the whole body was determined from its coordinate system using Poisson’s equation (Wittenburg, 1977). The pelvic moment was decomposed into three anatomical components in the pelvic coordinate system: lateral bending, flexion–extension, and axial rotation moments. The pelvic coordinate system was the same as that of the lower trunk for the DU BSP set (Table 2). Only the lateral bending moment was considered for the lateral bending task because this moment was the major component in the task. The flexion–extension moment and axial rotation moment were only considered for the flexion–extension and axial rotation tasks, respectively, for similar reasons.

Assessment of validity of the pelvic moment

The RMS difference between the pelvic moments determined using the top-down and bottom-up approaches, which will be referred to as the RMS error of the pelvic moment, was calculated for each task. The absolute difference in the peaks of the moments between the two approaches, which will be referred to as the absolute error of the peak moment, was also calculated for each task. Two peaks were observed in the pelvic moment curves for the lateral bending and axial rotation tasks and the peak with a larger absolute value was only considered for these tasks.
Trunk kinematics

To express trunk kinematics, the three markers of C7, SUP and PSUP defined the upper thoracic part. The three markers of RASIS, LASIS and MPSIS defined the pelvis. The orientation of the upper thoracic part relative to the pelvis was determined using Euler angles whose order of rotations was flexion-extension, lateral bending, and finally axial rotation. The angular velocity and acceleration of the upper thoracic part relative to the pelvis were also determined from the direction cosine matrices using Poisson’s equation and finite differentiation.

Statistical analysis

Effects of the three BSP sets on the RMS errors of the pelvic moment and absolute errors of the peaks of the moment were tested by one-way repeated measures analyses of variance (ANOVA). Multiple comparison tests with Bonferroni correction were used to make pairwise comparisons among the BSP sets when ANOVA results were significant. Effects of the three BSP sets and the two approaches on the peaks of the pelvic moment were tested by two-way (3 BSP sets × 2 approaches) repeated measures ANOVA. If an interaction was identified, simple main effects were tested. When the assumption of sphericity was not tenable as indicated by a Mauchly’s test, degrees of freedom were corrected using Hyunh-Feldt estimates of sphericity. A significance level was set at p < 0.05. SPSS Statistics Version 17.0 was used for all analyses.

Results

The maximum angles of the upper thoracic part relative to the pelvis were larger than
The maximum angular velocities were larger than 140°/s for all tasks.

The peaks of the pelvic moments occurred at about the changes of movement directions in all tasks (Figure 2). The top-down approach estimated a significantly smaller peak of flexion moment than the bottom-up approach (Table 4).

There were significant interactions of the BSP and approach effects for the peaks of lateral bending and extension moments (Table 4). For the lateral bending moment, the AE BSP set estimated a significantly larger peak than the DE and DU BSP sets in the bottom-up approach whereas the BSP had no significant effect on the peaks in the top-down approach. The two approaches did not provide significantly different peaks of the lateral bending moment in each of the three BSP sets. For the extension moment, the AE BSP set estimated a significantly larger peak than the DE and DU BSP sets in the top-down approach. In the bottom-up approach, the peaks of the extension moment estimated with the three BSP sets were different from each other although the differences among the sets were small. The top-down approach estimated a significantly smaller peak of extension moment than the bottom-up approach in the BSP set of DU.

The RMS errors of the pelvic moment were less than 10 Nm for most participants in all tasks and the mean RMS errors were less than 10 Nm for all tasks (Figure 3). The BSP sets had significant effects on the RMS errors for the lateral bending and axial rotation tasks, whereas there was no significant effect for the flexion–extension task. Post hoc tests revealed that the RMS error determined with the DE BSP set was smaller than that determined with the DU BSP set for the lateral bending and axial rotation tasks.

The mean absolute errors were less than 10 Nm in all tasks for all BSP sets except the
extension moment for DU (Figure 4). The effects of the BSP sets on all absolute errors were not significant.

**Discussion**

The maximum angles of the lateral bending (about 46º) and axial rotation (about 56º) observed in this study were larger than the matching normal values of maximum ranges of motion (40º and 40º, respectively), reported by Kapandji (2008). The maximum angles of flexion of 49º and extension of 32º in the flexion–extension task were much smaller than their matching maximum ranges of motion of 105º and 60º, respectively, reported by Kapandji (2008). The requirement to perform the tasks as quickly as possible may have limited the amount of motion in the flexion–extension task. The values reported by Kapandji (2008) were based on X-ray or computerized tomography techniques. The different angles between this study and that of Kapandji (2008) may be partly attributed to the difference in measurement technique. The angular kinematics shown in Table 3 would help determine whether the findings of this study can be applied to other motions (Lindsay & Horton, 2008).

The mean RMS errors of the pelvic moment were less than 10 Nm in all tasks for the three BSP sets. The mean absolute errors of the peaks of the moment were less than 10 Nm in all tasks for the AE and DE BSP sets (3.9–7.8% of the peak values). These magnitudes of the errors were comparable to the values reported for lifting tasks (Kingma et al., 1996; Plamondon et al., 1996; Larivière & Gagnon, 1999a). The results suggest that the pelvic moment can be determined for motions involving fast and large trunk movements with the same level of validity as for the lifting tasks using the top-down inverse dynamics approach, in which the trunk is modeled as two or three rigid-link segments.
Comparisons of the peak pelvic moments indicate that the top-down approach estimated a smaller peak flexion moment than the bottom-up approach in all BSP sets (Table 4). Peak flexion moment occurred at about the maximal extended position of the trunk. In this position, deformation of the trunk may cause a systematic error in the location of the trunk COM in the three BSP sets and eventually a smaller peak flexion moment. The accelerations of the trunk segments may have been underestimated owing to the deformation of the segments and the marker displacement relative to the underlying bone especially when the movement was changing directions. However, further investigations will be needed to verify these possibilities.

The differences in head and trunk inertia properties (Table 5) would at least partly explain the differences in peak lateral bending and extension moments among the three BSP sets (Table 4). The product of the mass and the square of the distance between the midpoint of both hip joint centers and the COM, which is related to the moments of inertia of the head and the trunk, was smaller in the DU BSP set than the AE and DE sets for the head and the trunk. A smaller moment of inertia generally leads to a smaller moment of force value. The peak extension moment determined using the top-down approach was smaller than that determined using the bottom-up approach in the DU BSP set. This seems to be related to the differences in BSP of the head and the trunk among the three BSP sets and suggests that the BSP sets of AE and DE were more appropriate than the set of DU for the participants of this study.

The RMS error of the pelvic moment and absolute error of the peak moment showed substantial inter-participant variability. The RMS error exceeded 10 Nm and the absolute error of the peak moment was about 30 Nm for some participants (Figures 3 and 4).
contrast, the RMS error and the absolute error determined with the BSP set of AE were both smaller than 5 Nm for the participant a. A likely cause of this is that each data set provided more accurate estimates of the inertial parameters of the upper body for some participants than for the others. The results suggest that an accurate estimation of the segment inertial properties is critical to accurately determine the pelvic moment using the top-down approach.

In this study, particular sets of the skin markers were used to determine the coordinate systems of the trunk segments (Table 2). The CAST method (Cappozzo et al., 1995) would make different skin marker sets available for the determination. Each trunk segment did not move as a rigid object in the trunk movements, in the strictest sense. Thus, it should be noted that locations of skin markers on the trunk segments might affect the error of the pelvic moment. Determining the locations of skin markers that minimize the pelvic moment error requires further investigation.

The characteristics of the participants investigated in this study limit its applicability to other participant populations, such as females and obese persons. Trunk morphology has been shown to affect errors in inverse dynamic analysis of the upper body in lifting tasks (Larivièere & Gagnon, 1999a). Thus, investigation using a population with high BMIs is needed in the future.

Acknowledgments

This work was supported by a Grant-in-Aid for Young Scientists (B) 19700497 from the Ministry of Education, Science, Sports, and Culture and Technology of Japan. The authors thank Inter-Reha Co., Ltd, which allowed us to use a VICON motion capture system.
References


Aerospace Medical Research Laboratory, Wright–Patterson Air Force Base, Dayton, Ohio.


Table 1 Three reference articles used to estimate the body segment parameters in this study.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Method</th>
<th>Number</th>
<th>Mean ± standard deviation</th>
<th>Race (nationality)</th>
<th>Profession</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ae et al. (1992)</td>
<td>stereo-photogrammetry</td>
<td>215</td>
<td>19.9 ± 1.1</td>
<td>Japanese</td>
<td>Collegiate athletes</td>
</tr>
<tr>
<td>McConville et al. (1980) adjusted by Dumas et al. (2007)</td>
<td>stereo-photogrammetry</td>
<td>31</td>
<td>27.5 ± 5.6</td>
<td>Unknown</td>
<td>US Air Force</td>
</tr>
<tr>
<td>Zatsiorsky and Seluyanov (1983) adjusted by de Leva (1996)</td>
<td>gamma rays</td>
<td>100</td>
<td>23.8 ± 6.2</td>
<td>Caucasian</td>
<td>Collegiate students</td>
</tr>
</tbody>
</table>

*Only data for male participants are listed for Ae et al. (1992) and Zatsiorsky and Seluyanov (1983).
Table 2 Definitions of the segment coordinate systems of the trunk segments for the three body segment inertial parameter sets and the markers used for the definitions.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Markers</th>
<th>AE: X</th>
<th>DE: Y</th>
<th>DU: Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper trunk</td>
<td>RSHO, LSHO, SUP, PSUP, RB, PRB</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td>the cross-product of Z-axis and the vector from RSHO to LSHO</td>
<td>the cross-product of Z-axis and the vector from LSHO to RSHO</td>
<td>the cross-product of Y- and Z-axes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the cross-product of Z- and X-axes</td>
<td>the cross-product of Z- and X-axes</td>
<td>the vector from LJC* to CJC*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the vector from the mid-point of RB and PRB to the mid-point of SUP and PSUP</td>
<td>the vector from the mid-point of XP and PXP to the mid-point of SUP and PSUP</td>
<td>the cross-product of the vector from CJC to SUP and Y-axis</td>
<td></td>
</tr>
<tr>
<td>Middle trunk</td>
<td>XI P, PXI P, NAB, PNAB</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td>the cross-product of Y- and Z-axes</td>
<td>the cross-product of Z- and X-axes</td>
<td>the vector from the mid-point of NAB and PNAB to the mid-point of XP and PXP</td>
<td></td>
</tr>
<tr>
<td>Lower trunk</td>
<td>RASI S, LASI S, MPSI S, RB, PRB</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td></td>
<td>the cross-product of Z-axis and the vector from RASI S to LASI S</td>
<td>the cross-product of Z-axis and the vector from LA S to RASI S</td>
<td>the cross-product of Y- and Z-axes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the cross-product of Z- and X-axes</td>
<td>the cross-product of Z- and X-axes</td>
<td>the vector from MPSI S to LA S</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the vector from the mid-point of both HPs to the mid-point of RB and PRB</td>
<td>the vector from the mid-point of both HPs to the mid-point of NAB and PNAB</td>
<td>the vector from LASI S to RASI S</td>
<td></td>
</tr>
</tbody>
</table>

AE: Ae et al. (1992); DE: de Leva (1996); DU: Dumais et al. (2007); *LJC is the lumbar joint center and CJC is the cervical joint center. Both joint centers were determined according to Reed et al. (1999). See the text for the other abbreviations.
Table 3 Maximum angles, angular velocities, and angular accelerations of the upper thoracic part relative to the pelvis during the tasks of trunk lateral bending, flexion-extension, and axial rotation.

<table>
<thead>
<tr>
<th></th>
<th>Lateral bending</th>
<th>Flexion-extension</th>
<th>Axial rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Maximum angle (°)</td>
<td>45.5 (r) 7.9</td>
<td>48.6 13.8</td>
<td>31.8 9.6</td>
</tr>
<tr>
<td>Maximum angular velocity (°/s)</td>
<td>209 48</td>
<td>201 67</td>
<td>145 40</td>
</tr>
<tr>
<td>Maximum angular acceleration (°/s²)</td>
<td>1335 933</td>
<td>1192 345</td>
<td>1183 330</td>
</tr>
</tbody>
</table>

r: right; l: left; SD: standard deviation.
Table 4 Peaks of the pelvic moments determined using the bottom-up and top-down approaches with the three body segment inertial parameter sets (Nm).

<table>
<thead>
<tr>
<th>Approach</th>
<th>BSP</th>
<th>Interaction</th>
<th>Lateral Bending</th>
<th>Flexion</th>
<th>Extension</th>
<th>Axial Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom-up</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Top-down</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>AE</td>
<td>156.9</td>
<td>27.0</td>
<td>159.0</td>
<td>30.1</td>
<td>156.7</td>
<td>26.9</td>
</tr>
<tr>
<td>DE</td>
<td>126.8</td>
<td>18.7</td>
<td>122.0</td>
<td>21.4</td>
<td>126.9</td>
<td>18.7</td>
</tr>
<tr>
<td>DU</td>
<td>188.1</td>
<td>31.6</td>
<td>194.8</td>
<td>32.9</td>
<td>187.3</td>
<td>31.6</td>
</tr>
</tbody>
</table>

* AE significantly different from DE and DU for the top-down approach; † three BSP sets were different from each other for the bottom-up approach; ‡ top-down approach significantly different from the bottom-up for DU; ‡‡ significant main effect of the approach; SD: standard deviation.
Table 5 - Inertial parameters of the head and whole trunk for the three body segment inertial parameter sets.

<table>
<thead>
<tr>
<th></th>
<th>AE</th>
<th>DE</th>
<th>DU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Head</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>4.3</td>
<td>0.6</td>
<td>4.3</td>
</tr>
<tr>
<td>COM distance from the midpoint of both hip joint centres, r (m)</td>
<td>0.740</td>
<td>0.034</td>
<td>0.737</td>
</tr>
<tr>
<td>Mass×r² (kg·m²)</td>
<td>2.4</td>
<td>0.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Whole trunk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>30.3</td>
<td>4.4</td>
<td>26.9</td>
</tr>
<tr>
<td>COM distance from the midpoint of both hip joint centres, r (m)</td>
<td>0.283</td>
<td>0.017</td>
<td>0.293</td>
</tr>
<tr>
<td>Mass×r² (kg·m²)</td>
<td>2.4</td>
<td>0.5</td>
<td>2.3</td>
</tr>
</tbody>
</table>

AE: Ae et al. (1992); DE: de Leva (1996); DU: Dumais et al. (2007); SD: standard deviation; Values were measured in upright standing postures.
Figure 1. A participant with markers.
Figure 2. Pelvic moments during the tasks of trunk lateral bending, flexion–extension, and axial rotation determined using the top-down and bottom-up approaches with Ae et al. (1992: AE), De Leva (1996: DE), and Dumas et al. (2007: DU) body segment inertial parameter sets and the angles of the upper thoracic part relative to the pelvis (left panels) for a typical participant (participant b). Values in the abscissa axis represent the time elapsed from the beginning of recording of the motion capture system.
Figure 3. Mean and individual root-mean-square (RMS) errors of pelvic moment during the tasks of trunk lateral bending, flexion-extension, and axial rotation determined with Ae et al. (1992; AE), De Leva (1996; DE), and Dumas et al. (2007; DU) body segment inertial parameter sets. *Significant difference between the BSP sets of DE and DU.
**Figure 4.** Mean and individual absolute errors of the peak pelvic moment during the tasks of trunk lateral bending, flexion–extension, and axial rotation determined with Ae et al. (1992; AE), De Leva (1996; DE), and Dumas et al. (2007; DU) body segment inertial parameter sets.