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Subject-specific body segment parameters' estimation using biplanar X-rays: a feasibility study

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ABSTRACT (169 words)

In order to improve the reliability of children's models, the aim of this study was to determine the subject-specific masses and 3D locations of the Centers of Mass (CoM) of body segments using biplanar X-rays. Previous methods, validated on upper leg segments, were applied to the whole body. Six children and 6 adults were studied. The low dose X-ray system EOS® was used to simultaneously get head-to-foot biplanar X-rays in the upright position. Specific methods were used to get 3D reconstructions of bones and body shape. The densities from literature were used to define the masses. To assess the accuracy of the reconstructions, a force plate was used to compare the mass and the projection of the CoM. A mean distance of 4.5mm between the measured and the calculated projections of the CoM was found. The mean error between the estimated and the actual body mass was 2.6%. Such a method will be useful in obtaining the body segments parameters in children, hard to obtain by direct measurements techniques.

Keywords: body segment; mass center; biplanar X-rays

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1. Introduction

Each year, 700 children die and 80,000 are injured on European roads (de Jager et al. 2005). According to Valent et al. (Valent et al. 2002), motor vehicle collisions are the leading cause of death among children older than 1 year. Child Restraint Systems (CRS) were specifically designed to optimize child protection: unbelted children under 3 have a 5.8 times greater risk of serious injury than those restrained in a child seat (Parenteau and Viano 2003). The use of an appropriate restraint system is associated with reductions in morbidity and mortality in this age group. CRS are continuously improved to decrease the seriousness of injuries. The car crash is still the most frequent blunt agent (Brown et al. 2006, García-España and Durbin 2008, Santschi et al. 2005).

In order to evaluate different protection systems, safety improvements are typically tested with crash dummies. For the design of adult dummies, dimensions, masses and Centers Of Mass (CoM) of adult body segments were obtained by a direct measurement on adults' corpses (Dempster 1955), stereo-photogrammetric technique (McConville et al. 1980), DXA (Ganley and Powers 2004), or regression equations (Dumas et al. 2007). Nevertheless, these methods are not applied for child dummies, because of the ethical issues. Furthermore, the injury criteria of Hybrid III and CRABI were defined as a scaling from the adult one (Mertz et al. 2003). Data were interpolated to estimate the dimensions at the desired age from the ranges of data available (Irwin and Mertz 1997, Schneider and Zernicke 1992, Wang et al. 2005). Some geometric databases were created to collect human-child-like dimensions, such as the Child Anthropometry Database, CANDAT, for the Q-dummies (de Jager et al. 2005, Saul et al. 1998, van Ratingen et al. 1997). Numerous studies were carried out to continuously improve the knowledge of child behaviour when a car crash occurs.

Body Segment Inertial Parameters (BSIPs) are also important in dynamic walking studies. A free oscillation technique was proposed in 1997 to determine the changes in moment of inertia due to child's growth, with a cylinder model, but only applied to the lower leg (Lebiedowska and Polisiakiewicz 1997). Another subject-specific estimation of body segment parameters, based on anthropometric measurements and digital images, was developed by Davidson et al. (Davidson et al. 2008). However, this method was validated with the forearm of only one subject. The mathematical model proposed by Jensen is based on 2cm wide elliptical zones, obtained by the digitization of photographic records, and used in many studies to establish regressions along the growth (Jensen 1978, 1986, 1989, Sun and Jensen 1994). In spite of these studies, the mass segment and the 3D CoM location are still not yet precisely available for children.

Methods were proposed in our lab in order to estimate BSIPs from biplanar X-rays (unpublished data, Dumas et al. 2005). The aim of this feasibility study, applied to the whole body, is to validate the subject-specific mass and 3D location of the CoM of children's and adults' body segments, using biplanar X-rays.

2. Materials and methods

Six healthy children (2 boys, 4 girls) aged from 9 to 13 and 6 young male asymptomatic volunteers aged from 22 to 26 took part in the present study. The low dose X-ray system EOS® (Biospace Instrument, Paris, France) was used to simultaneously get a pair of head-to-foot X-rays (Anteroposterior and Lateral – AP and LAT) of patients in upright position (Dubousset et al. 2005). A force plate was used to get the projection of the CoM and the mass during the X-ray acquisition. This protocol was approved from the ethical committee of Hôpital Pitié-Salpêtrière (Paris, France). The X-Rays were made on medical prescription for children (ethical committee approval CPP 06001). Adults were volunteers (ethical committee approval CPP 06036).The accuracy of the force plate was less than 0.3% on the mass and about 1.5mm for the position of the projection of the CoM. The height was assessed by a direct measurement on the calibrated radiographs.

Except for the upper limbs, specific reconstruction methods were used to get a validated 3D reconstruction of bones and body shape using a custom-made software (developed in collaboration between LBM (Arts et Metiers ParisTech-CNRS) and LIO (ETS-CRCHUM)) (Figure 1.a). Bone parts and body shape were reconstructed specifically for each subject. A semi-automatic identification of specific anatomical areas was performed on each AP and LAT radiograph. The 3D reconstruction algorithms have been described elsewhere: they are based on a first estimate of the shape and position of each segment (bone or skin) from a generic model and/or statistical data. Then, a deformation of this generic model was performed using the non stereo-corresponding points (NSCP) (Mitton et al. 2000), Pomero et al. 2004) and contours (NSCC) algorithms (Laporte et al. 2003). The algorithms reconstruction were consisted of 4 steps: the 3D contours' projection onto the radiographs, the associations between points of the X-rays' contours and the points of the projected 3D contours, the optimization of the initial solution and the optimized object deformation to minimize the distance between X-rays' contours and projected 3D contours.

For the body shape, the skin was identified on AP and LAT radiographs and automatically adjusted based on the pixel intensity gradient detection (Kass et al. 1988, Kauffmann et al. 1998). The 3D surface model used for the body shape reconstruction was computed from data obtained by a laser bodyscan on a young male volunteer (Anthroscan®, Human Solution). The same technique was used for bone parts (thoracic spine and rib cage). The accuracy of the bones' reconstruction was evaluated lesser than 1mm in previous published studies (Bertrand et al. 2008, Laporte et al. 2003, Mitton et al. 2008, Pomero et al. 2004).

The body shape reconstruction was divided in 11 segments: head, neck, thorax, abdomen, hip, thighs, legs and feet. The boundaries used for each segments were these described by Dumas et al. (Dumas et al. 2007), except for the distinction of the neck and the abdomen, not considered by Dumas et al' work. The head-neck delimitation was defined as being the horizontal plane through the center of the C1 vertebral body. The thorax-abdomen boundary was defined as being the horizontal plane through the most anterior superior point of the L3 vertebral body. The thoracic spine reconstruction was made in order to obtain the L3 vertebra and the rib cage (Humbert et al. 2009). The lungs' volume was defined using the rib cage reconstruction.

For each body segment, the 3D location of the CoM was calculated, assuming a homogeneous segment density. Table 1 details the densities applied to each volume to determine their masses (Dempster 1955, White et al. 1987). Because of the inside air, the lung density was defined in order to have a global density of the whole thorax (lungs and all the others organs inside the thorax) in accordance with the literature.

As the 3D reconstruction method is not yet accomplish for the arms, forearms and hands, these body segments were represented by rigid bodies. However, the masses and the CoM locations of the upper limbs are necessary for the global validation of the present method. Then, the positions of anatomical landmarks were digitized on the frontal and lateral radiographs: acromia, olecranons, wrist articulations and fingertip. Upper limb segments were then 3D reconstructed using DLT algorithms (Andre et al. 1994). The masses and CoM location of the arm, forearm and hand were calculated to assess the accuracy of the reconstructions. According to Dempster (1955) database, the CoM locations were then defined (Table 2), and the masses were calculated (Equations 1, 2 and 3).

Equation 1:

$$m_{arm} = 0.04017(m_{hip} + m_{thighs} + m_{abdomen} + m_{thorax})$$

Equation 2:

$$m_{forearm} = 0.02296(m_{hip} + m_{thighs} + m_{abdomen} + m_{thorax})$$

Equation 3:

$$m_{hand} = 0.00861(m_{hip} + m_{thighs} + m_{abdomen} + m_{thorax})$$

The total body mass was calculated by the addition of the masses of each virtual body segment. The global body CoM was defined as being the weighted barycenter of all segments' CoM. The accuracy of this model was estimated using the distance between the calculated and measured CoM projections, and the difference between the real and the estimated total body masses (Figure 1.b). In order to evaluate how errors in bone reconstruction affect the body segment estimates, sensitivity analysis was performed: as the boundary between the thorax and the abdomen depends on the reconstruction and 3D location of the L3 vertebra, the spines of the 6 children have been reconstructed 3 times by one observer. Then the thoraxes' and abdomens' volumes and CoM locations were modeled and compared. All differences between the 18 reconstructions were calculated.

3. Results

The mean error between the estimated body mass and the actual body mass was 2.6%-0.83kg (min: 1.1%-0.32kg, max: 4.6%-1.3kg) with a SD of 1.2%-0.37kg. The position of the center of mass projection calculated was spaced from the measured one with a mean of 4.5mm (min: 2mm, max: 10mm) and a SD of 3.2mm. The sensitivity study had shown, for the volumes, a mean difference equals to 0.02 dm3 (min 0.001 dm3, max 0.06 dm3, SD 0.02 dm3). That is for the thorax a mean equals to 0.25% (min 0.01%, max 0.71%, SD 0.20%); for the abdomen a mean equal to 1.22% (min 0.07%, max 3.11%, SD 0.89%). The segments' mass and the CoM locations for each body segment are presented in Table 3.

4. Discussion

With 6 children and 6 adults, the aim of the present study was to evaluate the feasibility and the accuracy of the method, to assess masses and CoM locations for children's and adults' body segments from biplanar X-rays. The method described is an extended and advanced version of previous techniques. The method used to obtain the 3D reconstruction of the body segments was already published (Laporte et al. 2003): the shape error (point to surface distances) is equal to 1.0mm (max 5.mm, RMS 1.4mm). Because no direct data related to children's body mass segment were found in the literature, an indirect method to evaluate the accuracy was proposed with the use of the total body mass and the projection of the global CoM.

Beyond the accuracy of the method itself, the location of bony anatomical landmarks (ALs) was dependent on the observer. Della Croce et al. in 1999 studied the position of selected bony ALs by palpation. ALs are not points but relatively large and curved areas. An Intra- and Inter- individual reproducibility study was performed in order to estimate the accuracy of ALs locations. Intra- and inter-examiner precision (RMS distance from the mean position) resulted in the range 6-21 mm and 13-25mm, respectively, i.e. a variability of 15 mm and 12 mm respectively. The accuracy of the X-ray method in locating bony landmarks was previously estimated (belonging to the rib cage). For example, Bertrand et al. evaluated in 2008 the intra- and inter- reproducibility of a 3D reconstruction method of the rib cage from biplanar X-rays. The interobserver variability in term of point-to-surface distances was equal to 5.1 mm (mean 1.9 mm).

Some limitations could be emphasized. The upper limbs were deduced from the literature, and segment densities of adults' corpses were used because children segment densities are still unavailable. Data were obtained assuming a constant and uniform density. This may introduce bias on the parameters. The global error might be underestimated because the validation was not made separately for each segment, but for the whole body. The overall CoM was an averaged value so errors on either side might cancel each other out. Furthermore, X-rays are limited to on medical prescriptions for children, this limitation could restrict the number and type of population group that can be analysed by the proposed method.

However, the accuracy results validated the feasibility of the proposed method. The accuracy is consistent with reports from similar studies. Most of the authors in the literature validated their methods with the comparison between a calculated total mass and the real one. Jensen found a range error of 1.16-1.82% with a photogrammetric method, an accuracy equal to 0.203% with photographic record and an error of 0.87% with an elliptical model (Jensen 1978, 1986, 1989). In the same way, Yokoi et al. obtained an error of about 3% for the location of the total body center of gravity obtained from photogrammetry and the reaction board method (Yokoi et al. 1986). Sun et al. obtained a mean error of 2.27% with an elliptical model. The close results between the mean values obtained in the present study for each adult body segment and the ones obtained by de Leva (1996) reinforce the reliability of the present method (Table 4). Furthermore, the present study suggests an additional original validation method with the comparison between the calculated and measured whole body CoM projection.

Accuracy could be increased by the differentiation of the bones and soft tissues, available in the literature (White et al. 1987), and by a better definition of the upper limbs. Taking different X-rays and CoM measurements of different poses may help to refine the accuracy assessment. Unfortunately, the width size of the X-rays is restricted and it will be difficult to have clear different postures. The segment volume could be estimated on living subject by water immersion, a convenient method proposed by Davidson et al. (2008). However, this method can be applied only on extremities segments, with perfectible boundary conditions: the exact conformity between the modeled segment and the boundary of the elbow at the surface of the water might be difficult to obtain. Future research could be done to increase the validation method: using a laser bodyscan device, leading to segment volume references. A complete sensitivity study to show how errors in bone reconstruction affect the body segment estimates could be done in the future. For the time being, the reconstruction is about one day by subject; it is mandatory to have a drastic time reduction to perform such a sensitivity study.

The proposed method has numerous advantages. It presents a subject-specific reconstruction and the calculated parameters are not derived from predictive equations. It also takes into account the possible non-symmetry of segments. The moments of inertia can be easily calculated from these reconstructions. Finally, the proposed method, focusing on children, enables to have subject-specific parameters which are described in the literature with approximations, and allows extensive data exploration. In comparison to photographic methods to measure body segment parameters, the X-rays acquisitions gave the possibility to have a precise reconstruction of the thorax in order to distinguish the lungs, which have a specific density because of the inside air (Figure 1.b.). The full potential of the X-rays had not been used in the present study. The main advantage of the X-rays is the access to all the other details which can not be available with simple photographic methods, like the bones geometry and location into the skeletal system. Future research is planed in order to develop whole body numerical models based on subject specific reconstruction. A fine reconstruction of the bones geometry could be made in order to improve the biofidelity of the models. All data will be available in only one X-ray acquisition.

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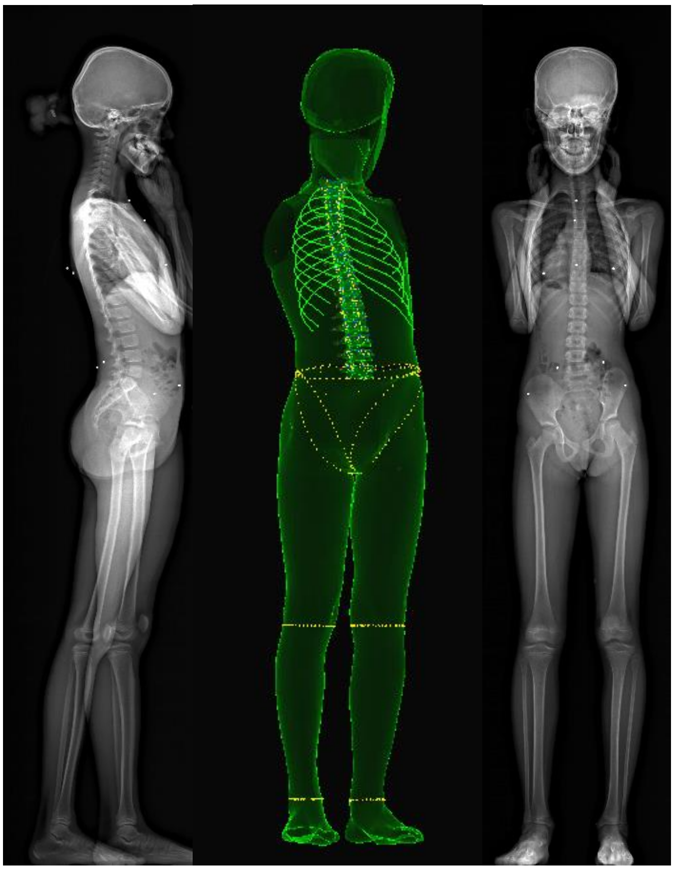

Figure 1.a. Subject-specific 3D child reconstruction – bones and body shape

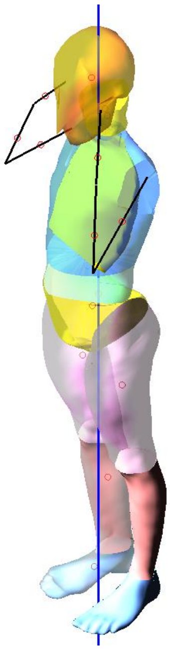

Figure 1.b. Subject-specific 3D child reconstruction – measured and calculated gravity line, CoM of each body segment is represented with a circle.

Table 1. Densities from literature used to obtain the mass of all various segments.

Segment	Density (g.cm^{-3})
Head	1.11
Neck	1.11
Thorax	0.92
Abdomen	1.01
Hip	1.01
Thigh	1.05
Leg	1.09
Foot	1.10

Table 2. Location of the upper limbs' CoM.

Segment and reference landmarks	Distance from reference to CoM
Hand (radio-carpal axis to 3rd dactylion)	36.2%
Forearm (ulno-humeral axis to radio-carpal axis)	43.0%
Arm (gleno-humeral axis to ulno-humeral axis)	46.8%

Table 3. Segments' mass and position of the CoM in children (n=6) and adults (n=6), SD is in parenthesis.

Segment	% of total mass - Children -	% of total mass - Adults -	Position of the CoM in % of total height - Children -	Position of the CoM in % of total height - Adults -
Head	8.8 *(1.3)*	4.6 *(0.4)*	93.9 *(0.4)*	92.8 *(0.4)*
Neck	1.3 *(0.3)*	1.3 *(0.3)*	87.9 *(0.7)*	86.9 *(0.8)*
Thorax	20.8 *(0.6)*	25.9 *(1.7)*	73.8 *(0.8)*	72.8 *(0.8)*
Abdomen	4.7 *(0.7)*	5.4 *(1.5)*	63.3 *(1.1)*	61.1 *(1.2)*
Pelvis	12.7 *(0.7)*	13.5 *(0.7)*	56.0 *(1.1)*	53.9 *(1.1)*
Thighs	26.3 *(2.1)*	26.5 *(2.5)*	42.6 *(1.5)*	40.7 *(0.6)*
Legs	10.3 *(0.4)*	8.9 *(0.5)*	18.6 *(0.7)*	16.9 *(0.4)*
Feet	3.6 *(0.2)*	2.9 *(0.2)*	2.3 *(0.7)*	2.1 *(0.1)*

Table 4. Mean data comparison of mass body segment, in percentage of total body mass.

<table>
<tr><th></th><th>De Leva (1996)</th><th>Present study</th></tr>
<tr><td>Gender</td><td>Men</td><td>Men</td></tr>
<tr><td>Number of subject</td><td>100</td><td>6</td></tr>
<tr><td>Age (year)</td><td>24</td><td>24</td></tr>
<tr><td>Mass (kg)</td><td>73</td><td>73.3</td></tr>
<tr><td>Head</td><td rowspan="2">6.94</td><td rowspan="2">6</td></tr>
<tr><td>Neck</td></tr>
<tr><td>Thorax</td><td rowspan="2">32.3</td><td rowspan="2">31.4</td></tr>
<tr><td>Abdomen</td></tr>
<tr><td>Pelvis</td><td>11.2</td><td>13.5</td></tr>
<tr><td>Thighs</td><td>28.3</td><td>26.4</td></tr>
<tr><td>Legs</td><td>8.6</td><td>8.9</td></tr>
<tr><td>Feet</td><td>2.7</td><td>2.9</td></tr>
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