Advancements of Methods for Fast and Accurate Estimation of Human Body Segment Parameter Values

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Abstract: In order to assess joint loads and to estimate joint reaction forces and net joint torques in human motion analysis, inverse dynamic approaches are commonly applied. These approaches rely on an accurate estimation of human body segment parameter values. The paper gives an overview of contemporary methods with a specific focus on approaches based on geometrical models, where image based or photogrammetric techniques are applied for estimating the parameter values fast and accurately.

1 INTRODUCTION

For the understanding of the cause of any movement the knowledge of patterns of forces acting on and within the human body is required. In general, forces are calculated indirectly using kinematic, kinetic and anthropometric data. A full kinematic description, accurate anthropometric measures, and external forces, are used to calculate joint reaction forces and net joint torques. This prediction is called an inverse solution and is a very powerful tool in motion analysis (Winter, 2005). Accurate estimations of human body segment parameter values (BSPs) are required to obtain accurate inverse solutions. These parameters comprise volume, mass, location of center of mass, principal moments of inertia and location of the principal axes of inertia. Studies (for example, Rao (2006)) have shown the sensitivity of inverse dynamic solutions to BSP.

2 AN OVERVIEW OF METHODS

Different approaches have been followed in order to determine human body segment parameter values. In the sequel, we will differentiate between statistical methods, methods based on medical imaging technologies, such as computerized-tomography (CT) or magnetic resonance imaging (MRI), methods based on geometrical models and dynamic parameter estimation methods.

2.1 Statistical Methods

Popular sources for BSP information are regression equations generated from human cadaver data (Dempster, 1955); (Clauser et al., 1969); (Drillis and Contini, 1966), which incorporate whole body and/or segment anthropometric measurements to predict BSPs. These equations provide quick and easy methods for human BSPs estimation, but have been criticized in several ways. An obvious problem of cadaver-based prediction is that they typically are based on data from a limited number of elderly cadavers, which may result in limited accuracy (cf. Nigg and Herzog (1999)). Erdmann and Kowalczyk (2015) propose a method for estimating volume, mass and location of center of mass of body segments based on regression equations developed by Erdmann (1997) using data from CT scans and Clauser et al., (1969). They put particular attention to the trunk, which is, according to Erdmann's (1997) method divided into subparts consisting of tissues of different density.

2.2 Methods based on Medical Imaging Technologies

Living-based, predictive models for BSP estimation involve the use of gamma ray scanning (Zatsiorsky, et al., 1990), CT (Ackland et al., 1988), MRI (Cheng et al., 2000), dual energy X-ray (Durkin et al., 2002), and combinations of methods. The approach of

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Durkin et al., (2002), for example, makes use of two X-ray intensities in order to determine bone material and soft tissue masses separately. Even though all these methods provide accurate BSPs estimations on living subjects, especially CT imaging and gamma-mass scanning, as well as X-ray methods underlie criticism because of the high costs and the radiation which the subjects are exposed to (cf. (Rossi et al., 2013).

2.3 Methods based on Geometrical Models

Geometrical models are based on geometric figure templates for segments. The exact shapes are defined by a certain number of anthropometric measurements. A popular model is that proposed by Hanavan (1964). 25 anthropometric dimensions are required for defining the shapes of all body segments. Another well-known and, to our knowledge, most accurate mathematical model for the computational estimation of BSP is the one published by Hatze (1979; 1980). The model ("hominoid") is based on 242 anthropometric input values. Hatze's model combines a volume and density function to estimate segment inertial parameters. Segments are sectioned into more than one shape, from which the volume can be estimated, to get more detail in contours of a body segment. In addition, this is coupled with a non-uniform density function. The hominoid model (see Fig.1) accounts for exomorphic and tissue density differences between males and females, segmental shape fluctuations and asymmetries in geometries of segments. There is, however, a high expenditure for the manual determination of the required input values. The direct measurement of the 242 anthropometric dimensions takes about 60-80 minutes.

2.4 Dynamic Parameter Estimation Methods

Methods of that kind are characterized by parameter fitting approaches based on kinematics and measured external forces.

We are aware of three notable developments, which have been published recently. Díaz-Rodríguez et al., (2016) apply a robotics formalism. They first estimate mass and center of gravity from a static model and include the results in a dynamic model in order to estimate the moment of inertia. Bonnet et al., (2016) identify the mass, center of gravity and moments of inertia over a number of static and dynamic postures using optimal exciting motions. Son et al., (2014) suggest a method based on the dynamic equation of motion. They perform consecutive steps using a commercial dynamometer. First, a quasi-static passive movement is executed, next a fast movement of the segment under investigation with and without addition of an attachment and finally of just the attachment. In both studies, however, inertial parameters have only been determined for selected segments.

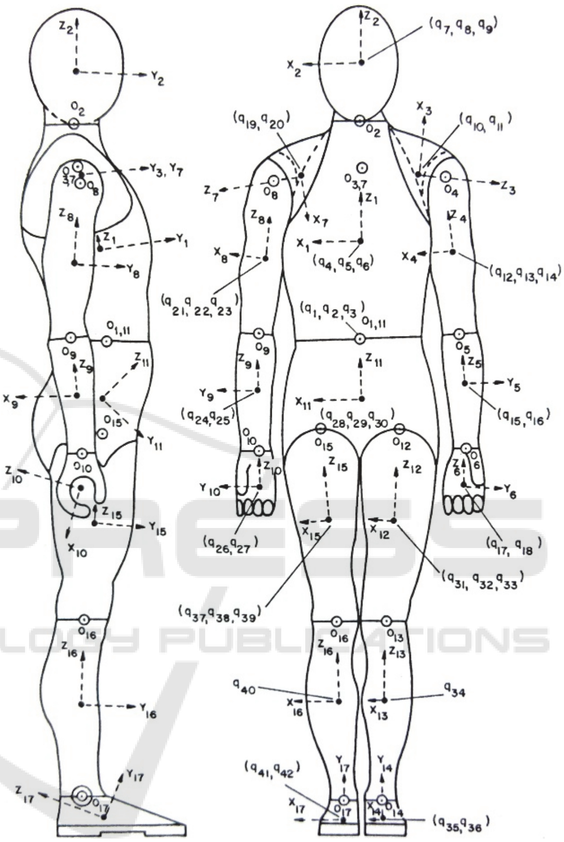

Figure 1: Hominoid. Adapted from (Hatze, 1983).

3 TOWARDS FAST AVAILABILITY OF SEGMENT PARAMETER VALUES

There is little debate that a geometric model with a non-uniform density function provides a very accurate BSP estimation. However, especially for clinical analyses of gait and posture non-invasive, safe, cost-effective and, in particular, rapid methods are from high importance in addition to providing accurate parameter values.

Image based or photogrammetric approaches provide means for capturing shape related data and the required geometric outlines without much effort. Clarkson et al., (2012) introduced a method based on a Microsoft Kinect based sensor system, whereas Peyer et al., (2015); Sheets et al., (2010) as well as Lu and Wang (2008) applied 3D body scanners.

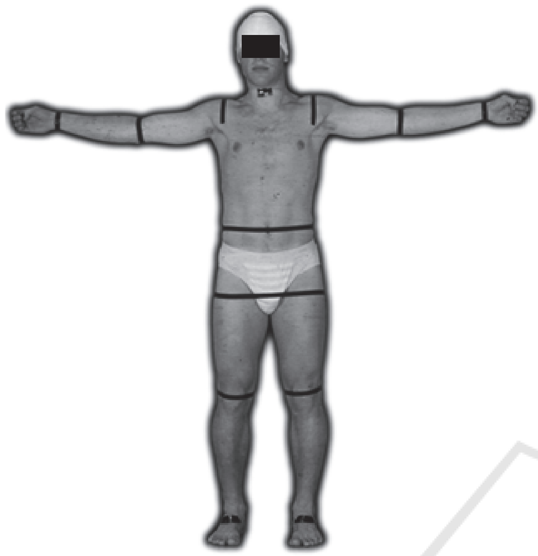

Figure 2: Video image for determination of anthropometric dimensions of hominoid model (cf. (Baca, 1996)).

3.1 A Video-based Approach for the Hominoid

In 1996, Baca introduced a method for determining the anthropometric data required for Hatze's hominoid (Baca, 1996). This method is accurate, but still somewhat time consuming, because several images from different planes have to be recorded. An example of one of the four recordings required is given in Fig. 2.

3.2 Application of 3D Scanners

The development of 3D scanners in the past decade has attracted several fields of science. Automated whole body scanner technology merged on the market offering the possibility of obtaining three-dimensional coordinates of measuring points on the surface of the object of interest fast, accurate and reliable.

By combining scanner based measurements and accurate mathematical segment models considering non-uniform density distributions both fast and accurate estimation of body segment parameters may be provided. The applicability of three-dimensional body scanning technology (Vitus Smart XXL, Vitronic, Wiesbaden, Germany) for determining automated or semi-automated individual anthropometric dimensions of Hatze's hominoid in order to determine subject specific body segment parameter values has therefore been investigated in the working group of the last author of this paper. The 3D body scanner used allows capturing full body scans with an accuracy of ± 1 mm. An example of a 3D-scan is shown in Fig. 3.

Figure 3: 3D-scan from Vitus Smart XXL 3D body scanner.

3.2.1 Automated Segmentation

The master thesis of Schiffl (2011) investigated the utility of the 3D scanner for the automatic segmentation of scan data into the 17 segments of Hatze's anthropomorphic model. Comparatively large differences were observed for the segment lengths and volumes (e..g. more than 20 % for the volume of the abdomino-thoracic segment) when determined as well manually as by applying the automated method.

3.2.2 A Semi-automated Approach

In order to overcome this problem, a semi-automated approach was followed in the master thesis of Cizgin (2013). The overall procedure for estimating all segment parameter values, which in total takes about 10-12 minutes, is as follows: First, the subject is prepared (clothing, bathing cap, 5 markers). Then, the subject is scanned in two different body postures. Whole body scans captured by Vitus Smart XXL, Vitronic 3D Body Scanner provide surface images as point clouds into the ScanWorX Software Solution (Kaiserslautern, Germany). The measurement module AnthroScan detects nearly all necessary landmark points relevant to Hatze's geometrical model automatically. The five landmarks which cannot be recognized accurately by the software (right jaw joint, most protruding point of left and right scapula, left and right hip joint center) have to be localized physically on the subject and marked with small circular markers before the scanning process. Once the surface image is visible as a 3D point cloud in the application, the user can position the relevant landmarks on the screen precisely guided through step by step introduction. Finally, the measurements, which should be performed disregarding subcutaneous fat in abdominal-pelvic section must be performed by direct measuring method. Because of this combination of automated calculation and user based positioning of icons, this approach is considered as a semi-automated determination. Furthermore, the application does not require any surface mesh procedures. The captured surface cloud point image is in sufficient detail and almost gap free reconstructed. By extending the implementation of the application, all Hatze relevant 242 subject specific anthropometric measurements can be automatically determined. Fig. 4 shown as an example represents the visualization of the virtual tape for taking the perimeters and length measures of the underarm and leg within the 3D scan image.

Mean absolute and/or relative differences (6 subjects) between the manual and the semi-automated approach for determining parameter values of selected segments are presented in Tab. 1. and Tab. 2. Both, negative and positive differences were found when comparing approaches. Deviations of more than 10 % were only observed in principal moments of inertia of small segments, which typically have limited influence on the result of analyses of whole-body motions.

The semi-automatic approach has shown to be suited for estimating human segment parameter values fast and accurate. The overall duration for one subject is about 12 to 15 minutes, whereas 60 to 80 minutes were required for the procedure based on manual measurements. A general drawback of methods based on the particular 3D scanner used lies in the comparatively high costs of the scanning device. It should, however, be possible substituting this specific instrument by scanners demanding lower costs (for example as described in Peyer et al., (2015), given that a similar scan resolution may be obtained.

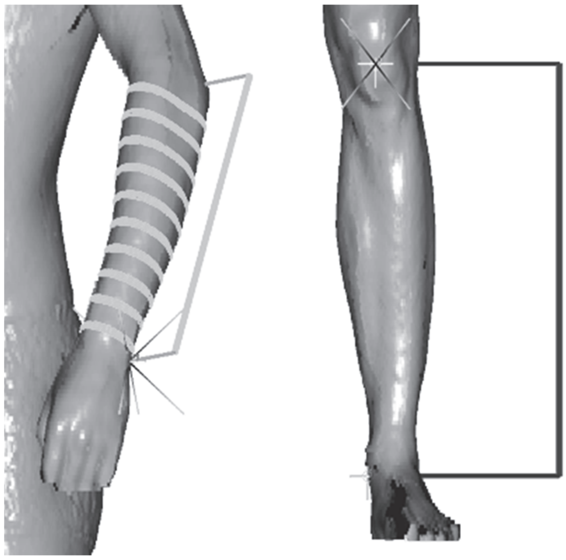

Figure 4: Virtual tape for taking perimeters and length measures.

Table 1: Mean relative and absolute differences (n=6) between length and mass obtained using manual measurement and semi-automated approach.

	length		mass	
segment	[%]	[mm]	[%]	[kg]
abdomino-thoracic	1,2	5,7	4,7	0,751
head neck	1,0	2,2	1,8	0,105
left shoulder	2,5	3,0	6,4	0,059
left (upper) arm	2,2	6,0	4,1	0,081
left forearm	2,4	6,3	4,2	0,054
left hand	2,6	2,2	7,6	0,023
abdomino-pelvic	1,9	4,8	2,1	0,302
left thigh	2,5	7,7	2,3	0,173
left leg	1,4	5,8	2,2	0,076
left foot	2,1	4,7	5,6	0,042

Table 2: Mean relative differences (n=6) between principal moments of inertia obtained using manual measurement and semi-automated approach.

	principal moments of inertia		
	x	y	z
segment	[%]	[%]	[%]
abdomino-thoracic	7,3	7,6	5,9
head neck	3,7	2,9	3,1
left shoulder	6,1	18,1	10,3
left (upper) arm	8,8	9,1	5,1
left forearm	7,2	7,1	7,9
left hand	10,8	21,0	17,7
abdomino-pelvic	7,3	4,1	6,9
left thigh	4,0	3,8	4,6
left leg	4,6	4,8	3,7
left foot	3,5	3,3	11,3

4 CONCLUSION

Geometric segment models combined with a non-uniform density function enable a very accurate BSP estimation. If anthropometric dimensions defining the shapes of these models are determined using three-dimensional body scanning technology, the overall parameter estimation process can be performed in some minutes. The semi-automated approach as described decreases time for data collection, whilst maintaining body segment accuracy when compared to the manual method.

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