THREE METHODS TO DETERMINE MASS CHARACTERISTICS OF HUMAN BODY SEGMENTS

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Three approaches to estimate body segment parameters (BSP) are compared, a volume-scanning photographic method, a force plate technique and a geometric method. First approach: a 3D body scanner was used to obtain a closed surface mesh of a subject. Closed loops were employed to divide the mesh into head, thorax, pelvis and limbs. Volume and center of mass (CM) of each segment were computed. Second approach: a triangular reaction board with two force sensors was used to measure the position of the CM. Third approach: The multi-body simulation software dynamicus/alaska models the segments by geometric shapes like elliptic solids, ellipsoids, and semi-ellipsoids. The results indicate that the body scanner method is highly accurate and an integration into dynamicus/alaska would increase simulation accuracy.

KEY WORDS: 3D body scanner, reaction board, alaska, center of mass

INTRODUCTION: Any kinetic analysis of human movement requires precise estimates of the BSP as mass, position of the center of mass and moments of inertia. Especially in gymnastics and diving biomechanical motion parameters are highly sensitive to the BSPs. Schleichardt, Schüler and Witt (2012) compared two BSP models with respect to the vertical momentum of the upper limbs during take-off in platform diving. They reported differences of more than 55% which emphasizes the necessity to use precise BSP models. A lot of pioneering work to explore regression formulas for mass-geometric parameters was done by Dempster (1955), Hanavan (1964), and Zatsiorsky & Seluyanov (1983). However, many regression formulas were based on few anthropometric data and on populations which are quite different from elite sports athletes.
The objective of this study was to overcome this drawback by proposing an individualized BSP estimation for a specific athlete. For this purpose a volume-scanning, a dynamometric and a geometric method are compared and eventually combined. The volume-scanning method, here referred to as the body scanner method, is based on the Poisson Surface Reconstruction described in Kazhdan, Bolitho and Hoppe (2006). This method is implemented in the body scanner software AnthroScan (HumanSolutions, 2005). It transforms the captured cloud of points – the surface of the subject – into a surface mesh represented by polygons. This mesh acts as the base for subsequent data processing as computation of segment volumes, segment lengths, circumferences and volume centers. The reaction board method is an indirect one similar to the ideas of Pataky, Zatsiorsky and Challis (2003). In the approach presented here the subject maintained different postures on the reaction board leading to quite different locations of his CM. These locations were exploited to determine segment masses. The geometric method uses specific solids for modeling segments similar to a modified Hanavan model studied by Kwon (1996). A total of 35 anthropometric data is required to construct this model which is implemented in the multi-body simulation software dynamicus/alaska (dynamicus, 2009). Uniform density throughout the segments is assumed in both the geometric and the body scanner approaches. This assumption was discussed by Ackland, Henson, and Bailey (1988) who reported only minor errors in estimation of inertial parameters of the leg segment.

METHODS: In this single case study a male subject of mass = 69.9 kg, height = 1.76 m and age = 33.8 years participated. For the body scanner method eight markers were used to tag acromion, superior iliac crest, anterior superior iliac spine and great trochanter. A 3D body scanner (Human solutions, 2005) was used to obtain a triangular mesh representing the shape of the subject. Closed loops on the mesh around neck, shoulder, elbow, wrist, thigh, knee and ankle were defined to separate the body segments (Figure 1, left, dotted lines).

Each loop is set up by two to five points on it. The shoulder loop meets the acromion and goes in superior-inferior direction. The loop which separates thigh from pelvis goes through the crotch and hip points. A horizontal loop through the two markers superior iliac crest (left and right) separates thorax and pelvis. Absolute segment volumes and absolute segment CM positions were computed by the scanner software. The distal and proximal axial endpoints of the limb segments were marked. They define the segment axis, the length of the segment and the relative CM positions.

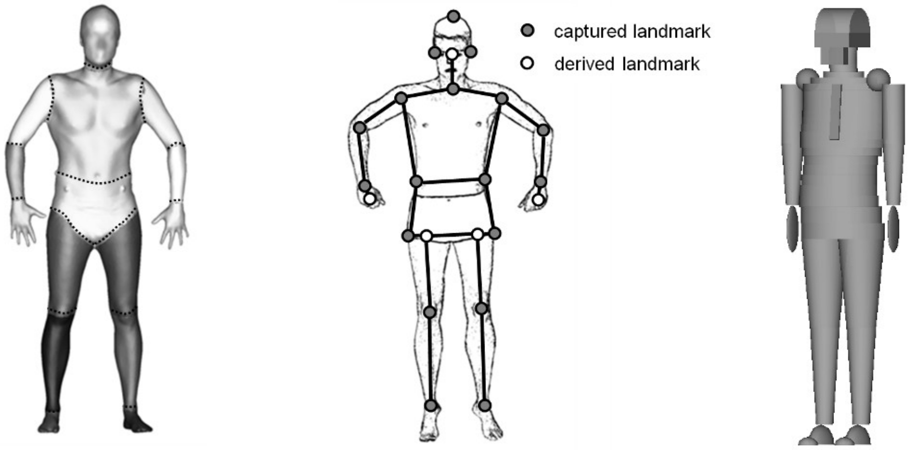

Figure 1: Left: Segmentation of the subject with body scanner software AnthroScan (Human Solutions, 2005). Center: Reaction board model. Right: Geometric dynamicus model.

The reaction board consists of an equilateral triangular board (side = 1.94 m) attached to two force sensors FS 1 and FS 2 situated in two vertices of the triangle. The third vertex of the board is fixed to the ground (Figure 2, left). The subject maintained 29 different postures on the board which were captured by a camera (Figure 2, right). Simultaneously the two voltage signals of the force sensors were recorded and converted into 2D coordinates of the center of mass. These coordinates served as input data for an optimization. For each posture 22 landmarks were digitized. The human body model consists of 15 segments, thorax, pelvis, thigh, shank, head, upper arm, forearm, hand, and foot (Figure 1, center). The relative segment masses $p_i = m_i/m$ were introduced, where m is the total mass and m_i is the mass of the i th segment. Note that the variables p_i are not independent since they add up to 1. The subject was assumed to have a symmetric left-right mass distribution. When we speak about coordinates and points we always refer to the 2D coordinates of the projection of the point into the reaction board plane.

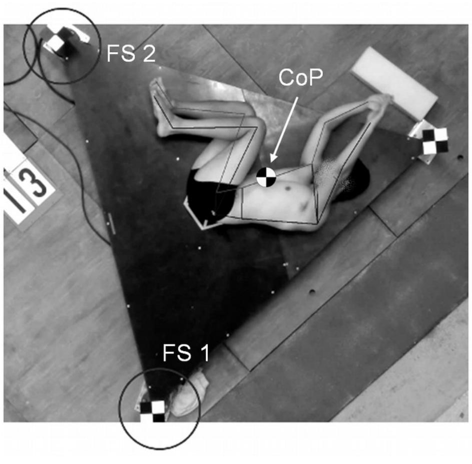

Figure 2. Left: Reaction board with two force sensors FS 1 and FS 2. The center of pressure (CoP) is the projection of the total CM to the board. Right: Three different postures with different CM positions.

The total center of mass is given by $CM = p_1 CM_1 + p_2 CM_2 + ... + p_{15} CM_{15}$ where CM_i are the segment CMs. Other variables q_i are introduced to determine the coordinates CM_i by the landmarks LM_{ij}. Considering the limbs the center of mass is a convex combination $CM_i = (1 - q_i) LM_{i1} + q_i LM_{i2}$ of the distal and proximal landmarks LM_{i1} and LM_{i2}. These landmarks can either be captured or derived (Figure 1, center). The variables q_i for thorax and pelvis can range freely, the other variables are fixed according to the values in Zatsiorsky and Seluyanov (1983). The least square optimization procedure *lsqcurvefit* of MATLAB was used to obtain the best fitting parameters p_i and q_i. Input to the geometric model are the mass as well as 35 anthropometric data, including heights of ankle, knee, great trochanter, vertex and length and circumferences of the limbs. The dynamicus models the limbs as elliptic solids (Figure 1, right). The thigh for example is defined by its length and the two ellipses at its proximal and distal ends.

RESULTS: Body scanner method. The described segmentation yields the following relative mass distribution (Table 1). The relative CM positions of the limb segments are almost equal about 40% proximal (Table 2). Reaction board method. The initial values for calculating the mass distribution were taken from body scanner measurement. The optimal mass distribution parameters p_i are shown in Table 1. The residual norm is the sum of all squares of all differences of the measured and the computed total CM coordinates. A residual norm of 0.0323 m^2 was obtained which corresponds to a mean error of 3.3 cm.

Table 1
Mass distribution of the subject determined with different methods compared with the regression of Zatsiorsky & Seluyanov (1983) in %

method	thorax	pelvis	thigh	shank	head	upper arm	forearm	foot	hand
body scanner	34.9	19.1	10.0	6.6	4.1	2.7	1.4	1.0	0.5
reaction board	35.5	14.9	11.0	7.5	4.1	2.8	1.4	1.2	0.5
dynamicus	36.2	10.5	13.1	8.1	4.3	2.4	1.5	1.1	0.4
Zatsiorsky & Seluyanov	32.3	11.2	14.2	6.9	4.3	2.7	1.6	1.4	0.6

Table 1 shows only small differences in relative mass distribution of shank, head, upper arm, forearm foot and hand. Also, the thorax ranges in a tight interval of 32.3 % (Zatsiorsky & Seluyanov) to 36.2 % (dynamicus). Comparing the four methods the body scanner overestimates the pelvis mass and underestimates the thigh. This is attributed to the position of the segmentation loop and gives a hint to modify segmentation instruction. However, the low thigh value of the body scanner is not critical since other authors see the relative thigh mass between 9.9 % and 12.2 % (Dempster, 1967).

Table 2
Distance of the segment CM to the proximal endpoint relative to the segment length in %

method	upper arm	forearm	thigh	shank
body scanner	40.2	39.3	40.5	40.5
dynamicus	48.3	41.8	41.8	41.3
Zatsiorsky & Seluyanov	45.0	42.6	46.1	40.3

In Table 2 one recognises large differences in the relative CM position of the upper arm. The geometric model (dynamicus) uses the smallest and the largest circumferences of the upper arm since the relative CM position of an elliptic solid depends only on the radii of the ellipses but not on the height. The body scanner, however, considers the true shape which is different from an elliptic solid near the shoulder.

DISCUSSION: The results indicate that pelvis and thigh are most sensitive to measurement errors and should therefore be treated with special care. The errors of the reaction board method are now estimated. While calibrating the board with ten different masses at four different points the gauge factors of the two force sensors differed by 1 % and by 2.5 %, respectively. The digitalization of the frames has an error of about 1 % for visible and at least 5 % for hidden landmarks. To improve the reaction board method, 3D analysis and the capture of more postures are inevitable. It turns out that the body scanner with a precision of 0.3 % for circumferences (Human Solutions, 2005) is the most reliable measurement device. Inaccuracies appear in the mesh reconstruction: filigree parts are cut and bridges enlarge the mesh.

CONCLUSION: Three methods to determine BSP have been compared. The advantage of the body scanner method is the accuracy in measuring volume and determining volume center. The reaction board measures weight forces which are directly related to masses. Density fluctuations between segments are respected and can be computed. The implementation of the geometric method into the multi-body modelling system dynamicus/alaska is a great advantage of the third method since the BSP can directly be used in the analysis of kinetic data. The combination of these three methods will be a powerful tool to determine individual body segment parameters. This tool needs to be further evaluated with more subjects and with its effect on the CM trajectory or on angular momentum. Prospectively individualized high accuracy simulations are expected to discover new sport technique aspects in elite sports.

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