Estimation of Arbitrary Human Models from Anthropometric Dimensions

Yui Endo(✉), Mitsunori Tada, and Masaaki Mochimaru

Digital Human Research Center, National Institute of Advanced
Science and Technology, Tsukuba, Japan
{y.endo,m.tada,m-mochimaru}@aist.go.jp

Abstract. In this paper, we describe a novel approach for reconstructing arbitrary whole-body human models from an arbitrary sparse subset of anthropometric dimensions. Firstly, a comprehensive set of dimensions is estimated from the subset via the principal component space for the dimensions. Then, a skin surface model with the obtained comprehensive set of dimensions is constructed by deforming a whole-body human model template. The result is validated based on the error distribution of the dimensions of the obtained surface mesh for the target.

Keywords: Human modeling · Anthropometry

1 Introduction

Over the past few years, "digital style design" for various kinds of products has been widely applied due to the spread of a variety of CAD systems. On the other hand, those designs with high ergonomic assessment such as easy shape and comfortable user-interface for human grasp and operation, so called "human centered design", have been receiving much more attention as this could enhance the market competitiveness of products. Current ergonomic evaluation processes require experiments based on a large number of various human subjects and a variety of physical mockups. These create bottlenecks in the product development cycle, are time consuming, have a high cost, and result in fewer implementations of ergonomic assessment. Thus, human models, digital models of various kinds of human, have been proposed to conduct the ergonomic assessment in a virtual environment. This virtual ergonomic assessment, integrating human models with product models, has a high possibility to produce ergonomic design quickly with less cost and its implementation has been highly anticipated.

Reconstruction of functional human models with arbitrary body shapes is the first step to conducting "virtual ergonomic assessment" in the process of human-centered product design. Thus far, we have proposed a reconstruction method of the human model and its postures for arbitrary individuals, conducted by inputting the trajectories of landmark points on the skin surface obtained from a motion capture system [1]. Though the human models obtained are accurate enough for our purpose, experiments with a motion capture system are too time-consuming and too expensive to be conducted for a plurality of real subjects.

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In this paper, we describe a novel approach for reconstructing arbitrary whole-body human models from an arbitrary sparse set of anthropometric dimensions. Though this method adopts an approximate approach by referring to the large database for whole-body anthropometric dimensions, it can be conducted much faster than the previously-proposed method.

2 Definitions and Methods

2.1 Human Model Definition

Thus far, we have developed the human models, called "Dhaiba", achieving the ergonomic assessment of products based on the precise simulation of various types of human size, shape and function in a virtual environment. The Dhaiba models include the "DhaibaBody", whole body models, and the "DhaibaHand", hand models (Fig. 1(a)(b)) [2].

Each Dhaiba model fundamentally contains the following three model elements:

1. A skin surface model consisting of as a triangular mesh which represents the skin surface in a reference posture.
2. A link model which includes a set of the local coordinate system of each joint and their connectivity as the links.
3. Each anthropometric dimension for the Dhaiba model is defined as the distance between two landmark vertices on the skin surface model. In some cases, the

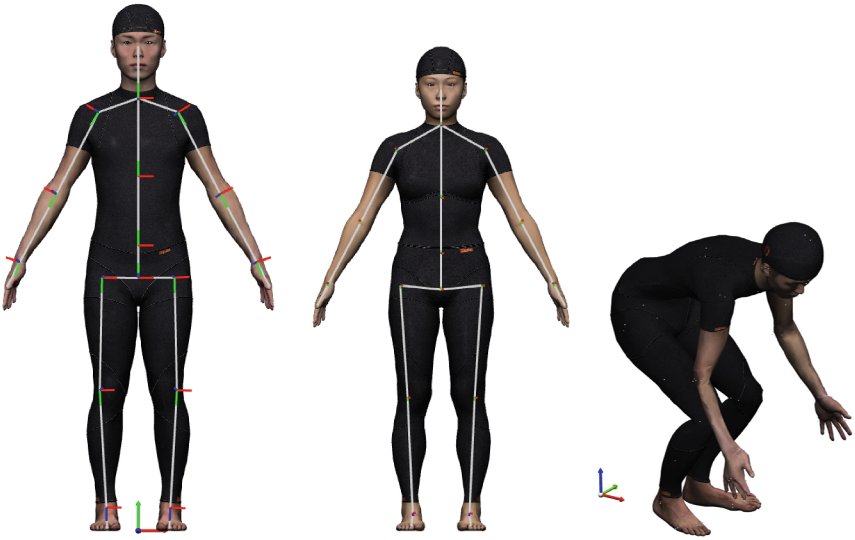
(a) (b) (c)

Fig. 1. The Dhaiba models. (a) The male template model, (b) the female template model and (c) the model which changed its posture.

distances along the *x*/*y*/*z*-axis in the world coordinate system are used as the definition.

The posture of the Dhaiba model is controlled by rotating the joint angles of the link model. The “Skeletal Subspace Deformation (SSD)” algorithm is used for the deformation of the skin surface model by following the joint rotation [3], so as to represent the whole-body geometry for arbitrary postures (Fig. 1(c)).

2.2 Overview of the Method

Figure 2 shows an overview of the proposed method. Firstly, the user specifies an arbitrary set of whole-body dimensions for a target, which is a subset of a comprehensive set of the dimensions. Then, the comprehensive set of the dimensions for the target is estimated from the input and a large database for the set. Finally, the human model for the target including the skin surface model and the link model is constructed by an optimization method based on the control of the “link scales”.

The details are described in the following sections.

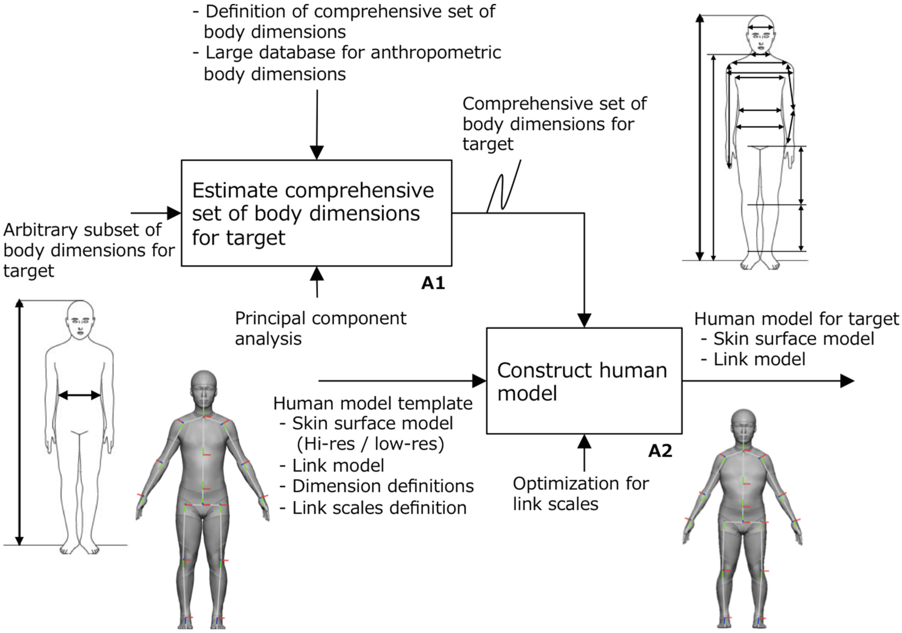

Fig. 2. Overview of the proposed method.

2.3 Estimation of the Comprehensive Set of Anthropometric Dimensions

The system performs the following steps to estimate a comprehensive set of anthropometric dimensions for the target from the arbitrary subset of the dimensions for the target.

2.3.1 Preparation

A large database for the comprehensive set of the whole-body anthropometric dimensions is prepared. A large dense matrix D is defined, where $D_{i,j}$, the (i, j)th entry of the D, represents the value of j-th dimension item for an i-th subject included in the database. Then a matrix X is calculated as the standardized matrix for the D:

$$X_{i,j} = \frac{D_{i,j} - \dot{a}_j}{\tilde{a}_j}, \tag{1}$$

where $\dot{a}_j$ and $\tilde{a}_j$ is the mean and the standard deviation for the j-th column of the D respectively. Hereafter we denote i-th row vector of the D the dimension vector $\mathbf{x}_i$. The correlation matrix C is calculated as follows:

$$C = \frac{1}{n-1} X^T X, \tag{2}$$

where n is the number of the columns of the X. Then the coefficient matrix W is calculated as the set of the eigenvectors for the C:

$$W = [\mathbf{e}_1 \quad \mathbf{e}_2 \ldots \mathbf{e}_n], \tag{3}$$

where $\mathbf{e}_1, \ldots, \mathbf{e}_n$ are the (column) eigenvectors related to the C. These vectors are sorted in descending order by their related eigenvalues.

2.3.2 Principal Component Analysis

By using the obtained matrix W, the dimension vector $\mathbf{x} = [x_1\ x_2\ \ldots\ x_n]^T$ can be mutually transformed into the n-dimensional column vector of the principal component scores $\mathbf{z} = [z_1\ z_2\ \ldots\ z_n]^T$ (the principal component vector) as follows:

$$\mathbf{z} = W\dot{\mathbf{x}}, \tag{4}$$

$$\dot{\mathbf{x}} = W^T \mathbf{z}, \tag{5}$$

where $\underline{\mathbf{x}} = [\dot{x}_1\, \dot{x}_2 \ldots \dot{x}_n]^T$ and $\dot{x}_j = (x_j - \dot{a}_j)/\tilde{a}_j$.

2.3.3 Estimation of the Dimension Vector

Here, the user chooses several dimension items from the complete dimension set and specifies values for them. By using these arbitrary n_s values in $\mathbf{x}$, the first n_s principal component scores can be estimated. For instance, in the case where $n_s = 2$ and the dimension item a and b are chosen as the subset, the approximate values of z_1 and z_2 are calculated as follows:

$$\begin{bmatrix} \dot{x}_a \\ \dot{x}_b \end{bmatrix} \cong \hat{W} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}, \tag{6}$$

where

$$\hat{W} = \begin{bmatrix} (W^T)_{a,1} & (W^T)_{a,2} \\ (W^T)_{b,1} & (W^T)_{b,2} \end{bmatrix}. \tag{7}$$

Thus, the following equation is obtained:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \cong \hat{W}^{-1} \begin{bmatrix} \dot{x}_a \\ \dot{x}_b \end{bmatrix}. \tag{8}$$

So, in this case, the approximate value of complete dimension vector $\mathbf{x}$ is calculated by Eqs. (5) and (8), where the other principal component scores $z_3, \ldots, z_n$ are set to zero.

2.4 Construction of the Human Model

In this section, the Dhaiba model for the target is constructed from the Dhaiba model template, based on the dimension vector $\mathbf{x}$ obtained in the previous section.

2.4.1 The Dhaiba Model Template

Construction of the Dhaiba model template is the first step to carrying out the optimization process for constructing the Dhaiba model for the target described in the following sections.

Figure 1 (a) (b) shows the Dhaiba model templates reconstructed from a dense polygon soup obtained by a laser scanner. The Dhaiba model for the target is obtained by deforming one of the template model, so the skin surface model and the link model for the target are “homologous” with the ones for the template. That is, the following are common among all Dhaiba models respectively:

1. The number of vertices, faces and the topological structure of the skin surface models
2. The vertex index of each landmark on the skin surface models
3. The structure of the link models

2.4.2 Skin Surface Deformation Based on Link Scales

Once the Dhaiba model template is prepared, the shape of the template model can be dynamically changed by controlling the “link scales”.

The link scale $s_{j,k}$ is defined as a variable for an axis k ($k \in \{+x, -x, +y, -y, +z, -z\}$) of each joint j of the link model. Based on the link scales, the origin of the local coordinate system Σ_j for each joint j is updated as follows:

$$\mathbf{o}'_j = {}^{W}T'_{j-1}\, S(j, \mathbf{o}_j)\left({}^{W}T_{j-1}\right)^{-1}\mathbf{o}_j, \tag{9}$$

where $\mathbf{o}_j = [o_{jx}\ o_{jy}\ o_{jz}\ 1]^T$ is the position vector of the origin of the Σ_j and $\mathbf{o}'_j$ is the updated one. ${}^{W}T_{j-1}$ is the 4 × 4 matrix which transforms the world coordinate system into the local coordinate system Σ_{j-1} ($j-1$ indicates the index of the parent joint of the j) and ${}^{W}T'_{j-1}$ is the updated one. The 4th column vector of ${}^{W}T_j$ is updated from $\mathbf{o}_j$ to $\mathbf{o}'_j$ and ${}^{W}T'_j$ is obtained as the result. $S(j, \mathbf{v})$ is the 4 × 4 scaling matrix defined as follows:

$$S(j, \mathbf{v}) = \begin{bmatrix} s_{j,x'} & & & O \\ & s_{j,y'} & & \\ & & s_{j,z'} & \\ O & & & 1 \end{bmatrix}, \quad \left(\mathbf{v} = [v_x\ v_y\ v_z\ 1]^T\right), \tag{10}$$

where

$$x' = \begin{cases} x & (v_x \geq 0) \\ -x & (v_x < 0) \end{cases}, \quad y' = \begin{cases} y & (v_y \geq 0) \\ -y & (v_y < 0) \end{cases}, \quad z' = \begin{cases} z & (v_z \geq 0) \\ -z & (v_z < 0) \end{cases}. \tag{11}$$

On the other hand, the position of each vertex v on the skin surface model of the template is updated as follows:

$$\mathbf{v}' = \sum_j w_v^j\, {}^{W}T'_j\, S(j, {}^{j}\mathbf{v})\left({}^{W}T_j\right)^{-1}\mathbf{v}, \tag{12}$$

where $\mathbf{v}$ is the position vector of the v and $\mathbf{v}'$ is the updated one. w_v^j is a vertex weight of v for the link bound to the joint j, which represents the degree of the relation between each vertex on the skin surface model and each link. This weight set is also used as the parameter of the skeletal subspace deformation method (a.k.a. the linear blend skinning) [3]. For calculation of the weight set, we use the skin attachment method based on heat equilibrium [3].

Figure 3 shows an example of the relation between the link scales, the modified link model and the deformed shape of the skin surface affected by the link scales.

2.4.3 Optimization Method for Constructing the Target Human Model

By using the comprehensive set of anthropometric dimensions for the target obtained in Sect. 2.3, the system optimizes the body shape of the Dhaiba model template by controlling the link scales and obtains the Dhaiba model for the target. This nonlinear optimization problem is represented as follows:

1. The link scales for the link model of the Dhaiba model template are the variables. Based on the change of the link scales, each local coordinate system of the link model and each vertex position of the skin surface model is updated.
2. The comprehensive set of anthropometric dimensions obtained for the target should be satisfied as the constraints. As described in Sect. 2.1, each dimension is

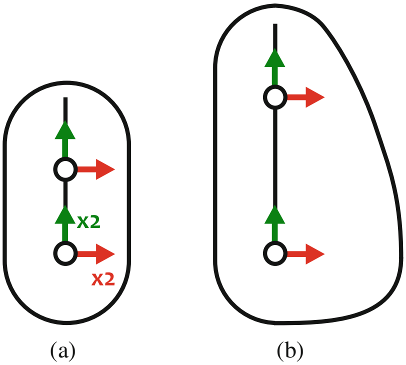

Fig. 3. The effect of link scales in the human model deformation. (a) The original shape and (b) the deformed shape. In this case, the link scales for the +*x* (red) and the +*y* (green) axis of the root joint are set to 2.0.

calculated as the distance between two landmark points on the skin surface model. Euclidean distance or the distance along x/y/z-axis is used as the definition of these distances. In this study, the following kinds of the dimensions are not used as the constraints: (1) dimensions which were not measured with the standard standing position and (2) ones which can not to be represented as linear distances.

3. The following energy function E is used as the objective function to be minimized:

$$E = c_S E_S + c_I E_I + c_V E_V, \tag{13}$$

where c_S, c_I and c_V are user-specified coefficients. E_S and E_I are the energy functions defined in the correspondence optimization algorithm [4]. E_S, deformation smoothness, indicates that the transformations for adjacent triangles should be equal. E_I, deformation identity, is minimized when all transformations are equal to the identity matrix. E_V is the variance of the link scales.

3 Results and Discussion

An anthropometry database for Japanese adults collected in the national project called “size-JPN” in 2004–2006 [5] was used for the estimation of the comprehensive set of the anatomical dimensions, described in Sect. 2.3. This database includes results of the anthropometric measurements of 217 dimensions for 6,700 Japanese 18–80 year old subjects. Figure 4 shows distribution of the mean errors and the coefficients of variation of the estimated comprehensive set of dimensions. We picked up comprehensive sets of dimensions for 500 randomly chosen subjects from the database, and, by using the body height and the body mass of each set as the input, each comprehensive set of the dimensions was estimated from the method proposed in Sect. 2.3.

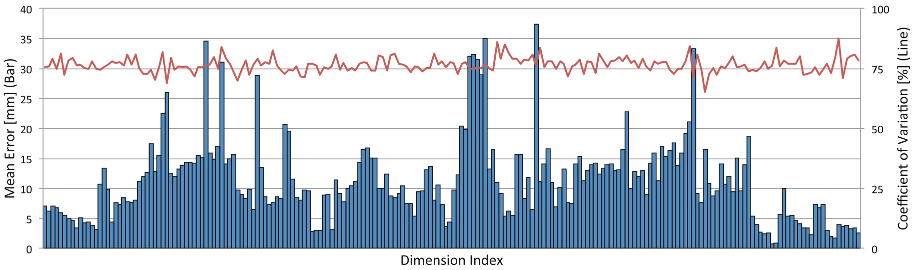

Fig. 4. Distribution of the mean errors and the coefficients of variation of the estimated comprehensive set of dimensions.

Figures 5 and 6 shows the construction result of the Dhaiba models for several targets and their error distribution of the dimensions of the obtained models. The process described in Sects. 2.3–2.4 was done in 6–7 s for each target.

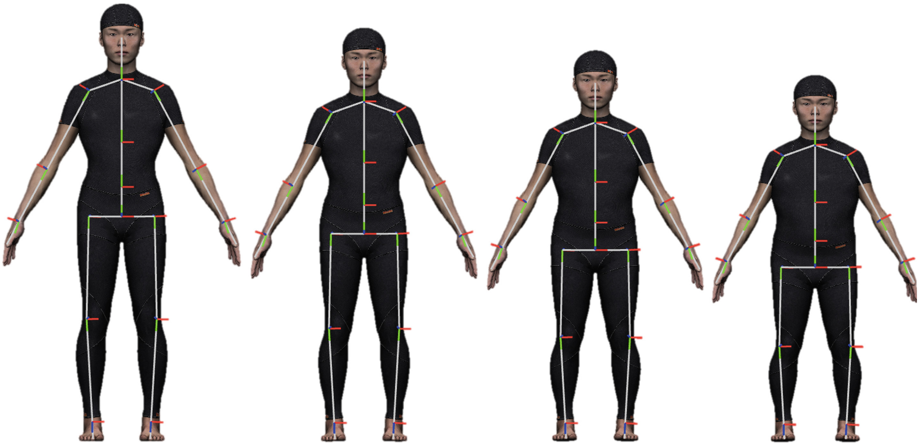
(a) (b) (c) (d)

Fig. 5. Constructed Dhaiba models for several targets. Height and weight were specified for each construction as the input. Specified height was (a) 1800 mm, (b) 1700 mm, (c) 1600 mm and (d) 1500 mm. Specified weight was 67.93 kg, mean value of Japanese 30–34 year old males.

The method deforms the target mesh to satisfy the dimension constraints while keeping the details of the mesh shape, so the initial shape of the template model has a major effect on the result. Therefore constructing the appropriate template models is one of the critical issues for obtaining good results. In addition, there is a wide variety of individual whole-body shapes, so, though we currently use single template model for any target, we need to prepare several kinds of the template models and select an appropriate model suitable for the target shape.

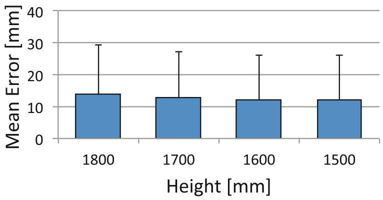

Fig. 6. Mean errors and their standard deviations of the dimensions of the obtained models for the estimated dimensions (the input of the method described in Sect. 2.4).

4 Conclusions

In this paper, we proposed a novel approach for reconstructing arbitrary whole-body human models from an arbitrary sparse subset of anthropometric dimensions. The comprehensive set of dimensions was estimated from the subset via the principal component space for the dimensions. The skin surface model with the obtained comprehensive set of dimensions is constructed by the optimization of the shape of the whole-body human model template based on the link scales control.

Annex A. Comprehensive Set List of Anatomical Dimensions

Table 1 shows the comprehensive set list of the anatomical dimensions which we used for the proposed method in Sect. 2.3.

Table 1. The comprehensive set list of the anatomical dimensions. H: height, L: length. * means the dimension is used as the optimization constraints described in Sect. 2.4.3.

Stature, p (body H, p)*	Right shoulder angle of slope 1 (acromion)	Side neck to anterior waist L via nipple
Body mass (weight)	Right shoulder angle of slope 2	Nipple to anterior waist L
Total head H*	Left shoulder angle of slope	Shoulder to anterior waist L
Pupil to vertex H*	Right nipple to fossa jugularis distance*	Fossa jugularis to anterior waist L, p
Tragion to vertex H*	Left nipple to fossa jugularis distance*	Waist to hip L
Stomion to vertex H*	Bust base angle	Outside leg L
Stomion to tragion H*	Thigh L*	Posterior waist to hip L (belt waist)
Gnathion to glabella H*	Lower leg L*	Posterior waist to hip L (horizontal waist)
Face L*	Neck breadth*	Gluteal arc

(*Continued*)

Table 1. (*Continued*)

Stature, p (body H, p)*	Right shoulder angle of slope 1 (acromion)	Side neck to anterior waist L via nipple
Gnathion to pupil H*	Shoulder (biacromial) breadth*	Gluteal arc, putting leg up
Gnathion to stomion H*	Shoulder (bideltoid) breadth*	Total crotch L
Head L*	Anterior biaxillary breadth*	Upper posterior arm L, elbow flexion
Head breadth*	Elbow-to-elbow breadth	Total posterior arm L, elbow flexion
Bitragion breadth*	Angulus inside by scapulae horizontal distance*	Total posterior arm L
Bizygomatic breadth*	Angulus inside by scapulae linear distance*	Cervicale to wrist L via shoulder and elbow
Interpupillary breadth*	Angulus inferior by scapulae horizontal distance*	Side neck to shoulder L
Head circumference	Angulus inferior by scapulae linear distance*	Posterior shoulder L
Sagittal arc	Nipple to nipple breadth*	Posterior chest L
Bitragion arc	Bicristal breadth*	Anterior shoulder L
Stature (body H)*	Biiliospinale anterius breadth*	Anterior chest L
Eye (pupil) H*	Chest breadth*	Sitting H
Eye (lateral canthus) H*	Bust breadth*	Eye (lateral canthus) H, sitting
Gnathion H*	Waist breadth*	Gnathion H, sitting
Cervicale H*	Abdominal breadth*	Cervicale H, sitting
Side neck H*	Hip breadth (peak of buttock)*	Shoulder H, sitting
Fossa jugularis H*	Hip breadth (maximum lower body)*	Elbow H, sitting
Shoulder H*	Armscye width*	Dactylion H, over head, sitting
Anterior axillary H*	Chest depth*	Abdominal extension H, sitting
Radiale H	Thorax depth at the nipple (bust depth)*	Trochanterion H, sitting
Dactylion H	Waist depth*	Thigh clearance, sitting
Elbow H	Abdominal depth*	Thigh H, sitting
Fist (grip axis) H	Hip depth*	Knee H, sitting
Dactylion H, over head	Hip depth, p	Knee joint H, sitting
Angulus inside by scapulae H*	Thigh depth*	Lower leg L (popliteal H), sitting
Angulus inferior scapulae H*	Knee depth*	Sitting surface H
Mesosternale H*	Calf depth*	Buttock-knee L, sitting
Nipple H*	Neck circumference	

(*Continued*)

Table 1. (*Continued*)

Stature, p (body H, p)*	Right shoulder angle of slope 1 (acromion)	Side neck to anterior waist L via nipple
		Buttock-popliteal L (seat depth), sitting
Waist H*	Neck base circumference	Buttock-trochanterion L, sitting
Posterior waist H*	Chest circumference	Buttock-abdomen depth, sitting
Anterior waist H*	Chest circumference at nipple level (bust circumference)	Hip breadth, sitting
Omphalion H*	Waist circumference 1 (horizontal waist)	Abdominal depth, sitting
Lower waist H*	Waist circumference 2 (belt waist)	Lower limb L, sitting
Iliocristale H*	Lower waist circumference	Hand L*
Abdominal extension H*	Iliocristale circumference	Palm L perpendicular*
Iliac spine H*	Abdominal extension circumference	Index finger L*
Trochanterion H*	Hip circumference	Hand breadth, diagonal*
Peak of buttock H*	Hip circumference, p	Hand breadth at metacarpals*
Maximum lower body breadth H*	Armscye circumference	Index finger breadth, proximal*
Gluteal furrow H*	Upper arm circumference	Index finger breadth, distal*
Crotch H*	Elbow circumference	Hand circumference
Maximum thigh circumference H*	Forearm circumference	Fist circumference
Mid-patellar H*	Wrist circumference	Foot L 1*
Knee joint H*	Inguinal circumference	Foot L 2*
Tibial H*	Thigh circumference	Tibial instep L*
Maximum calf circumference H*	Knee circumference	Fibular instep L*
Ankle H*	Calf circumference	Foot breadth 1, diagonal*
Span	Ankle circumference	Foot breadth 2*
Upper limb L*	Drop	Heel breadth*
Upper arm L*	Scye depth, p	Heel circumference
Forearm L*	Cervicale to posterior waist L, p	Instep circumference
Shoulder-elbow L	Cervicale to posterior hip L, p	Foot circumference
Forearm-fingertip L	Posterior full L, p	Instep circumference maximum H*
Elbow-grip L	Cervicale to side neck L	Foot circumference maximum H*
Arm reach from back	Cervicale to nipple L	Ball H*

(*Continued*)

Table 1. (*Continued*)

Stature, p (body H, p)*	Right shoulder angle of slope 1 (acromion)	Side neck to anterior waist L via nipple
Grip reach; forward reach	Cervicale to anterior waist L via nipple	Big toe outside angle
Wall-acromion distance	Cervicale to fossa jugularis L via side neck	Little toe outside angle
Elbow-wrist L	Side neck to fossa jugularis L	Sphyrion H*
Side neck to acromion horizontal distance*	Side neck to posterior waist L	Lateral malleolus H*
Side neck to acromion vertical distance*	Shoulder to posterior waist L	Sphyrion fibulare H*
Side neck to acromion linear distance*	Side neck to nipple L	Bimalleolar breadth*

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