Automatic anthropometric personalization of a digital human model from a set of subject's photographs

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Abstract. The objective of the work is to develop a method for automatic dimensioning of a digital human model (DHM) from a set of calibrated photographs of the subject under study. Fifteen subjects (10 males, 5 females, mean age 27) wearing surface retro-reflective markers at major bony landmarks and standing inside a calibrated space, were photographed by means of low cost main stream digital cameras (face, left and right views). The DHM software used is based on a skeletal structure surrounded by contours defined by cross sections along the skeletal links. Specific points corresponding to bony landmarks are defined in body linkage local reference frames. The photograph calibration method (DLT) allows to superimpose a picture of the DHM on the subject's photographs. A specific algorithm adjusts the length of the manikin skeletal links in function of the measured distance between markers attached to these links (e.g. knee and ankle for the lower leg). Then the contour sections dimensions were adjusted to fit subject's silhouette extracted from the photographs. The results obtained within a few seconds of calculation consist of a personalized DHM representing the subject with an error less than 2% for stature and less than 4% for weight.

Keywords: Anthropometry, digital human model, personalization, photographic

1. Introduction

The biomechanical analysis of a human being in a work situation or interacting with a product can be facilitated by the use of a digital human model (DHM). The relevance of the collected data relies on the accuracy with which the model represents the observed subject from a biomechanical point of view.

Commercially available DHM software offer modules allowing the dimensioning of the manikin from a set of standard anthropometric measures. Besides the time required by the collection of numerous data and the risk of errors introduced by the manual method, the resulting manikin does not always closely match the original subject [1].

The objective of the work presented is to develop an automatic method to derive the dimensions of a numerical manikin (skeleton and contours) from a set of calibrated photographs of the subject under study.

2. Methods

2.1. Subjects

Fifteen young healthy adults, 11 males and 4 females aged 27±7 years, involved in an experiment dealing with movement analysis in a driving task were included in the study. The subjects wore light underwear and 32 retro-reflective markers (10 mm diameter) were fixed to the skin surface (or on the clothing in some places) indicating the location of major palpable underlying bony landmarks so that these points could be located in space by means of a motion capture system. The location of the anatomical points was determined according to the guidelines of Van Sint Jan [2].

The main anthropometric dimensions were recorded by standard methods [3] then the subjects were photographed under four views (face, back, left and right) inside a calibrated space bounded by 4 vertical

calibration bars. These bars bear reflective markers laid according to a different pattern on each bar in order to be automatically identified on the pictures. The subjects were asked to maintain a standing posture with arms and legs slightly off the torso axis.

2.2. Photographs calibration

The photographs were taken with low cost mainstream cameras. The resolution was limited to 1500 x 2000 pixels. The calibration is based on the DLT method [4] using the bar markers. For this, the 2D coordinates of these markers on the photographs and the 3D coordinates in the laboratory frame are needed. The detection of markers on each photograph is automatically obtained by applying a threshold value of 250 for a 0-255 pixel coding range. Then, the 2D position of the marker is given by the barycentre of the identified white pixel zone.

2.3. 3D marker coordinates

The 3D coordinates of the markers fixed on the subject and on bars were obtained by means of a Vi-con® motion capture system. But these coordinates can be extracted from the photographs by means of the DLT method if a motion capture is not available. This alternative was used to locate extra body landmarks which were not indicated by surface markers (tragions, nasion and finger tips). The bar marker coordinates can also be known just from a known positioning of the bars.

2.4. Manikin (DHM)

Structure : The manikin used (see Fig. 1), Man3D [5], comprises a tree like skeleton whose root is located at the pelvis level and which is composed of 55 links, 52 joints and 102 degrees of freedom (dof), half of these being located in the hands. The contours attached to the links are constituted by triangular facets defined by transverse cross sections along the skeletal link longitudinal axes.

Anatomical points: the manikin comprises also specific points corresponding to the surface markers located indicating the anatomical landmarks. All these points are defined by their coordinates in the local reference frame attached to the skeletal links. These coordinates are normalized with respect to the main dimensions of the body link to which they belong (anterior-posterior depth, lateral width and lon-

gitudinal length). A constant term is added in order to introduce the offset of markers with respect to the skin surface. Some of these coordinates have been derived from the literature (Reynolds [6] and Seidel [7] for the pelvis, Salmon [8] for the head) and have a statistical significance.
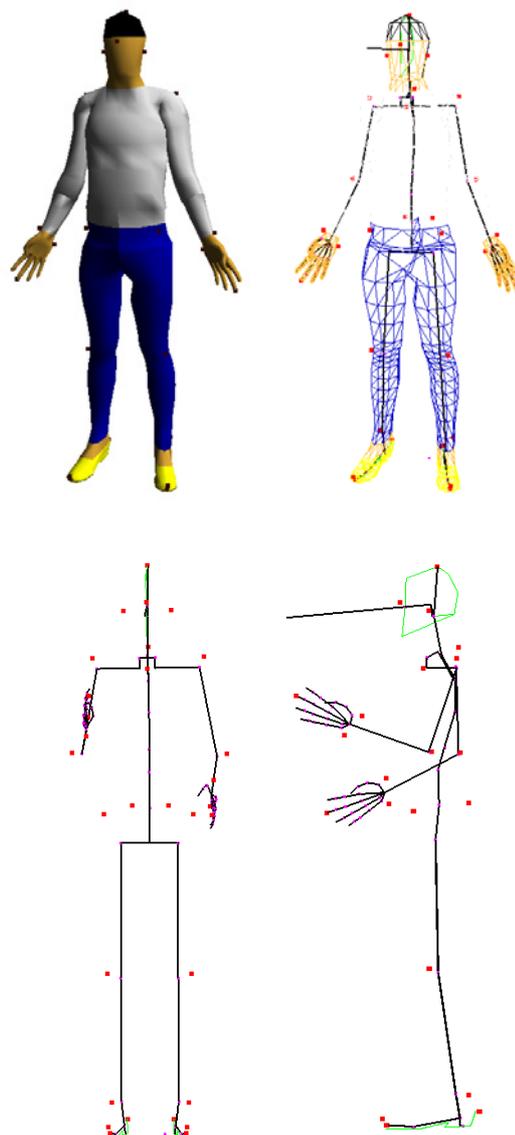
Fig. 1 Man3D, the DHM used to represent the subjects. a) wireframe mode, b) rendered mode, c) stick figure mode with anatomical landmarks

The others have been collected on bone radiographs and don't have any statistical value. The actual coordinates of the markers are obtained by mul-

tiplying the local normalized coordinates by the dimensioning factor and projecting them in the general reference frame.

The coordinates and dimensioning factors of the anatomical points are given in Table 2 at the end of the document.

2.5. Body profile

The subject's body 2D profile was manually created by drawing a polyline matching the body contour on each photograph. It takes 2-3 minutes to click 200-250 points to create the profile line and no specific skill is required. An automatic contour extraction module is being developed in order to avoid this manual operation.

2.6. Adjustment procedure

. The calculated DLT parameters allow the calculation of projection parameters of a manikin drawing onto the subject's photograph.

The adjustment consists in modifying first the dimensions, the position and the orientation of the skeletal links of the manikin. In a second phase, the manikin contours are modified in order to fit the subject's profile line on at least two views (face and left). Lateral symmetry of body dimensions is assumed.

Dimensioning principle: In the manikin, all points are defined by their local coordinates normalized with respect to the main dimensions of the body link to which they belong. As shown on Fig. 2, the length L of a body link (e.g. the shank) can be adjusted as a function of the distance D_m between two surface markers M_1 and M_2 (e.g. external knee and external ankle markers). These markers correspond to bony landmarks B_1 and B_2 respectively. The relationship between D_m et D_B (D_B is the distance between B_1 and B_2) is not necessarily linear and the adjustment is repeated as long as the difference between D_m et D_B remains greater than a prescribed threshold ε. The corresponding algorithm written in pseudo code is shown in the frame below Fig. 2.

Positioning principle: with at least 3 markers, one can estimate the 3D pose of a body link (see for instance [9]). But, in the manikin, links are connected to their parent by joints with either 1, 2 or 3 dofs. Knowing the pose of the parent link, according to the number of dofs, one or two markers are enough to determine the pose of the child link.


```
Dm=||M1M2||
Do While abs(Dm-DB) >ε
        DB=||B1B2||
        K=Dm/DB
        L=L x K
        Update B1, B2
End do
```
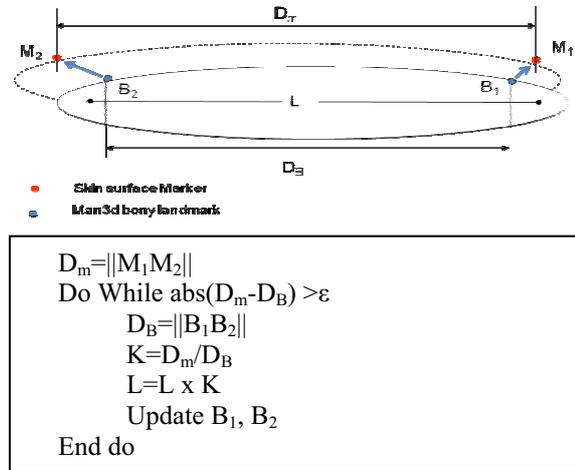
Fig. 2 Body link dimensioning. L is the link length, D_m the distance between two surface markers M_1 and M_2, D_b the distance between the two corresponding bony landmarks B_1 and B_2. The algorithm used to adjust L is listed in pseudo code in the lower box.

Sequencing of operations: The dimensioning and positioning process is applied to the body links according to the flow chart of Fig. 3. The process starts at head level then continues by locating the pelvis. At least three points are used for these links. Then, the process goes on with the limbs. On the graph, each step corresponds to a box and the markers used are indicated on the side as input to the box.

Contour adjustment: The components of the body link are projected on the image plane on which the profile line was drawn. For each contour section, a deformation vector V_{def} is defined in the image plane, perpendicularly to the projection of the longitudinal axis of the body link (see Fig. 4).

The contour points of the section are projected on this vector. The extreme points E1 and E2 on each side of the section allow the calculation of the initial dimension of the projected contour section. The intersections E_1' and E'_2 between V_{def} and the profile lines define the target dimension for the contour section. Then each point P of the section is modified according to the change in the dimension. The v component of vector CP (C is the center point of the contour section) along V_{def} is multiplied by a coefficient K equal to the ratio $||CE'||/||CE||$. In fact, contour sections are represented by polygons with 12 vertices for the torso and 8 vertices at limb level. If the photographs are taken along orthogonal axes practically aligned with the body axes, for most of the sections the outmost vertices fall on Vdef..
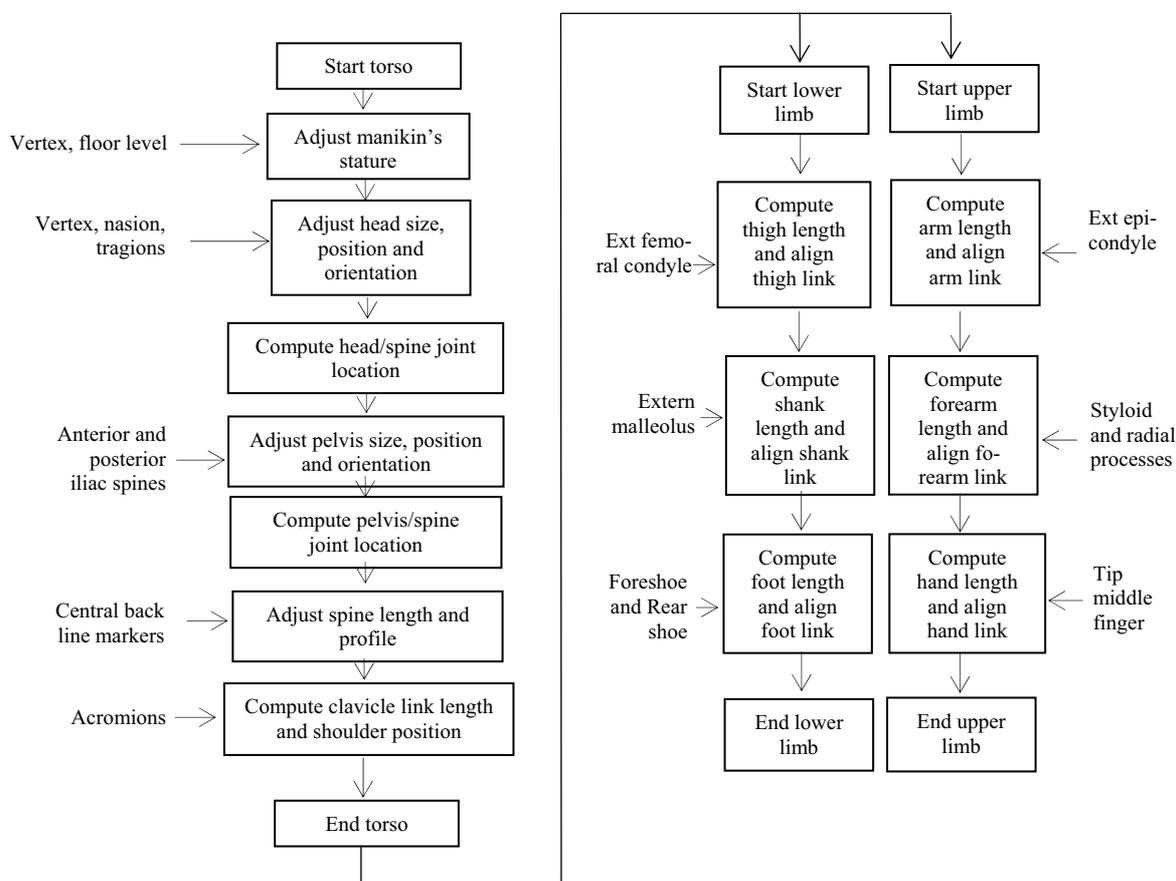
Fig. 3 Flow chart of body link dimensions and position calculation. The input points are indicated on the side of each calculation box.

But if there is some rotation of the link along its longitudinal axis, the outmost vertices are out of V_{def} and a small error in the dimensioning occurs The contour adjustment is performed on at least two views, face and left. For the face view, only one profile line is provided. For the side view, two separate lines are provided, one for the torso and lower limb and another one for the upper limb. This will be an issue to solve for the contour extraction module.

Computation of anthropometric dimensions: the anthropometric dimensions are computed between vertices of the adjusted contour mesh and /or anatomical points. The circumferences are estimated by the perimeter of the closest contour section. Two specific postures have been defined, as close as possible to the standard postures for anthropometry measurement. The first is standing with parallel legs and elbows flexed at 90 degrees, the second one is sitting erect with also elbows flexed. Body mass is com-

puted from the volume limited by the contours and from a set of volumic mass values found in the literature [10]. These values are listed in Table 1.

Table 1

Distribution per body region of volumic mass values used to compute body mass

Body segment	Volumic mass (g/ml)
Head	1.0710
Neck	1.0420
Thorax	0.9200
Shoulder	1.0700
Abdomen/pelvis	1.0100
Thigh	1.0500
Shank	1.0900
Foot	1.1000
Upper arm	1.0700
Forearm	1.1300
Hand	1.1600
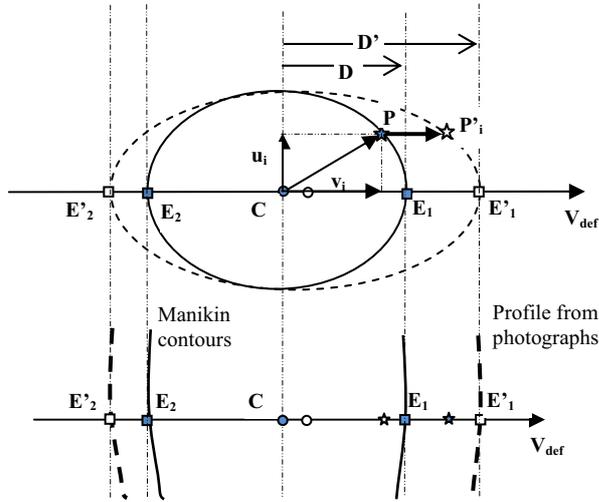
Fig. 4 Adjustment of contour sections against profile extracted from photographs (see text)

3. Results

Fig. 5 shows a sample of the results obtained for a male subject. The pictures show from left to right : a) the body silhouette alone; b) the subject's photograph with the silhouette superimposed; c) the skeletal structure adjusted to the subject; d) the adjusted contours in wireframe mode; e) the contours in rendered mode. On average, the position of surface markers is reached with an error of 13.74 mm (see Fig. 6). The differences between calculated and measured anthropometric values are indicated on the graph of Fig. 7. Stature with shoes on is estimated with a mean deviation of 1.59 mm but with a standard deviation of 17.7 mm. The maximum error is as high as 33 mm. Body mass is systematically overestimated with an average difference of 2.36 kg (std. dev.=1.15). The largest deviation is recorded for chest depth which is 28 mm.

a b c d e
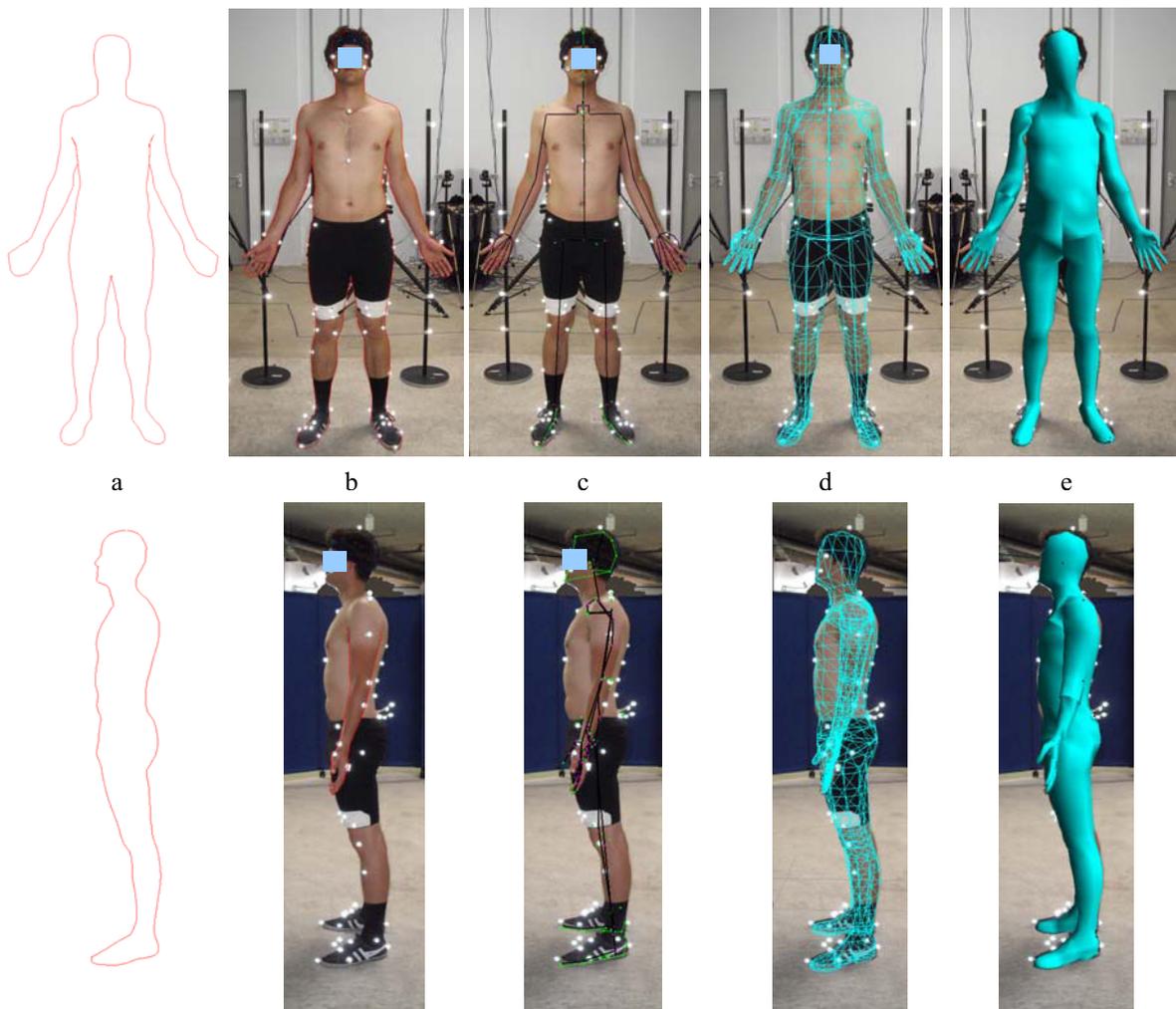
Fig. 5 Illustration of the steps followed in the adjustment process of the posture, dimensions and contours of the manikin. From left to right are displayed: a) the body silhouette alone; b) the subject's photograph with the silhouette superimposed; c) the skeletal structure adjusted to the subject; d) the adjusted contours in wireframe mode; e) the contours in rendered mode
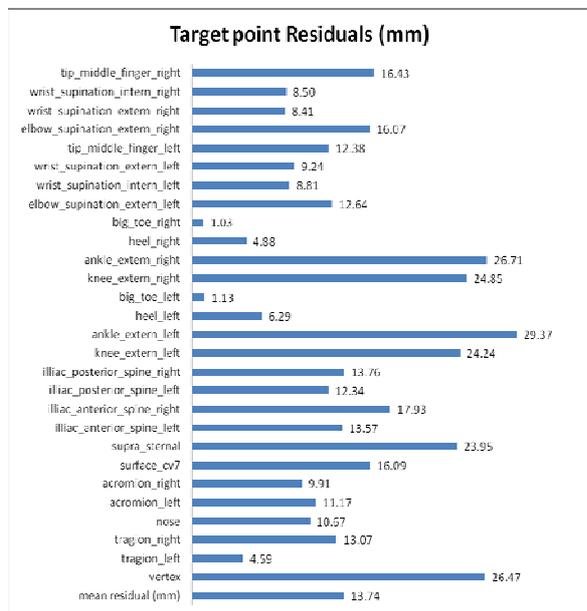
Fig. 7 Position error on calculated target points

Fig. 6 Error on calculated anthropometric data

4. Discussion

Despite the good fit of the adjusted model to the subject's photographs, the computed deviations from target points and anthropometric variables remain important. This is quite surprising because direct measurements of points on the photographs are pretty accurate on the calibration object for instance or on subject's shoes. Several reasons can be mentioned to explain these differences.

Concerning the anatomical points, the assumption was made that they can be calculated by applying to generic normalized coordinates a dimensioning factor along each body segment reference axis. Beside the approximate character of the used values, the natural scatter of that kind of data among the population and the uncertainty about their dependency on the overall dimensions of the concerned body segment probably do not allow reaching the target points with a good accuracy. This assumption is likely insufficient but few data can be found in the literature to support an improvement of this definition. An attempt to derive better values for the 96 dimensioning parameters (32 points x 3 coordinates) from an optimization procedure is being conducted but did not yield results so far.

The biofidelity of the skeletal model is also a source of errors. Indeed, simplifying hypotheses concerning the joints between certain body segments introduce constraints that can be incompatible. For instance, in the manikin, the elbow flexion axis is assumed perpendicular to the plane passing through the gleno-humeral, the elbow and the wrist joint centers. This provision which neglects the abduction of the forearm relative to the upper arm is not an issue when the purpose is to simulate a generic human. But, when an accurate representation of a real subject is intended, this simplification prevents from meeting the exact geometry. Introducing an inclination of the elbow flexion axis produced a better posture of the upper limb. But this angle, which varies from one individual to another should be part of the adjustment parameter set for personalization.

The anthropometric dimensions calculated on the adjusted mesh are also quite different from those directly measured on the subject's body by standard methods. Several causes can be invoked to explain these differences. The first one is that the mesh of the manikin contours is sparse; as a whole, 1696 vertices define the contour mesh including 576 for both hands only. This low density makes that for several subjects, the minimum waist circumference falls between two torso contour sections. A finer mesh would prevent this type of problem.

The shape of contour sections is generic and comes from cadaveric data. The adjustment concerns only the main dimensions of the sections but not the position of the vertices. Since, the vertices position condition the body volume, it affects the body mass calculated.

More important, the contour adjustment was made for a specific posture, different from those usually adopted to perform anthropometric measurements. Stature can change if the posture on photographs is more relaxed as compared to the standard measure, back resting on a plane. If other skeletal dimensions are not modified, in principle by posture change, soft tissues dimensions may be changed, especially in the abdomen and pelvis area. Currently, some of the geometric changes of the posterior face of the pelvis area when hip flexion occurs are modeled in the manikin; but this modeling is still insufficient.

The large difference in chest depth measurement found its explanation in the fact that for the standard measurement, subjects were instructed to expire as fully as possible while they were naturally breathing when they were photographed.

The accuracy on calculated anthropometric dimensions is much lower than that obtained with modern full body scanners [11]. But here, the goal is not only to obtain anthropometric dimensions but provide a fully functional sized manikin; this introduces some constraints that are sources of errors.

5. Conclusion

A method was developed to automatically adjust the skeleton and contours of a digital human model from at least two photographs of a real subject taken in a calibrated space. The method was applied to a sample of 16 subjects, male and females and provided a realistic representation of these subjects. The accuracy on the anatomical point position and on the calculated anthropometric dimensions can probably be improved through a better definition of the coor-

dinates of anatomical landmarks and through the use of a finer and more realistic mesh.

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Table 2

Definition of the anatomical landmarks and user points coordinates in the local skeletal link reference frames.
Local coordinates are obtained by multiplying the coefficient by the dimensional parameter value.
(D=anterior-posterior depth, W=lateral width, Z=length of the skeletal link

	axis	X		Y		Z	
	Link	Par dim	coeff	Par dim	coeff	Par dim	coeff
1	AcromLeft	clavicle_left	clav_length	0	clav_length	-0.25	clav_length	0.1
2	AcromRight	clavicle_right	clav_length	0	clav_length	0.25	clav_length	0.1
3	AntSupIllSpineLeft	pelvis	Z_pelvis	0.7	ill_breadth	0.5	Z_pelvis	0.75
4	AntSupIllSpineRight	pelvis	Z_pelvis	0.7	ill_breadth	-0.5	Z_pelvis	0.75
5	Cv7	upper_thorax	Z_upp_thor	-0.8	Z_upp_thor	0	Z_upp_thor	0.97
6	ExtElbowLeft	upper_arm_left	D_forearm	-0.2	W_forearm	-0.3	Z_upp_arm	1
7	ExtElbowRight	upper_arm_right	D_forearm	-0.2	W_forearm	0.3	Z_upp_arm	1
8	ExtWristLeft	forearm_left	D_wrist	0	W_wrist	-0.5	Z_forearm	1.02
9	ExtWristRight	forearm_right	D_wrist	0	w_wrist	0.5	Z_forearm	1.02
10	ExtKneeLeft	thigh_left	D_knee	0.05	W_knee	-0.4	Z_thigh	0.97
11	ExtKneeRight	thigh_right	D_knee	0.05	W_knee	0.4	Z_thigh	0.97
12	ExtAnkleLeft	shank_left	D_foot	-0.08	Z_shank	-0.09	Z_shank	1.02
13	ExtAnkleRight	shank_right	D_foot	-0.08	Z_shank	0.09	Z_shank	1.02
14	ElbowPostLeft	upper_arm_left	D_forearm	-0.5	W_forearm	-0.1	Z_upp_arm	1
15	ElbowPostRight	upper_arm_right	D_forearm	-0.5	W_forearm	0.1	Z_upp_arm	1
16	IntWristLeft	forearm_left	D_wrist	0	W_wrist	0.5	Z_forearm	1.02
17	IntWristRight	forearm_right	D_wrist	0	W_wrist	-0.5	Z_forearm	1.02
18	Nasion	head	D_head	0.55	W_head	0	Z_head	0.3375
19	PostIllSpineLeft	pelvis	Z_pelvis	-0.83	ill_breadth	0.13	Z_pelvis	1.1625
20	PostIllSpineRight	pelvis	Z_pelvis	-0.83	ill_breadth	-0.13	Z_pelvis	1.1625
21	SupraSternalNotch	upper_thorax	D_thorax	0.3	Z_upp_thor	0	Z_upp_thor	0.9
22	TipMidFingerRight	mid_finger_right	Z_digit34	0	Z_digit34	0	Z_digit34	1
23	TipMidFingerLeft	mid_finger_left	Z_digit34	0	Z_digit34	0	Z_digit34	1
24	TragionLeft	head	D_head	0.075	W_head	0.5	Z_head	0.1125
25	TragionRight	head	D_head	0.075	W_head	-0.5	Z_head	0.1125
26	Vertex	head	D_head	0	W_head	0	Z_head	1