Realistic Modelling of Individual 3D Figurines Using Body Measurements

Wilfried Grabbe * and the working group Pvifig [1]

Universitaet Bremen
Dept. Mathematics/Computer Science

Abstract

This paper deals with a new approach for modelling virtual figurines from body measures of a person that are ascertained conventionally, primarily by means of tape measure and ready-to-wear sizes. By relating measurement points to the vertices of a few basic 3D models of figurines and thereupon adapting vertex distances to the measure data, a replica of that person can be build as an interpolation of the basic models.

In comparison to currently available body modelling methods, the proposed new approach enables an improved computation of realistic figurines without considerable need for initial time and familiarisation to modelling software. It also opens up further possibilities e.g. in the field of virtual try-on of clothing.

Key words: figurine; virtual model; body measurement

1 Introduction

The computation of realistic models of a human body in virtual space is a subject which opens up new fields of research for science and inspires the industry to create new products due to its wide spectrum of applications. Rather frequently it gives rise to certain synergy effects, which also apply to the procedure of modelling individual figurines based on body measurements described from Section 3 onwards: This procedure emerged from the task to enable an ordinary PC user to build a precise virtual model of his own body in short time, without being forced to do substantial investments, comprehensive

* Corresponding author.
Email address: `wgrabbe@informatik.uni-bremen.de` (Wilfried Grabbe).

[1] All members are listed in App. C.

studies or extensive installations in advance. The applications are many and diverse: In virtual worlds of computer adventures or internet chat systems for example the participant's avatars could be more personalized. Quite new forms of design and presentation environments for ready-to-wear products would be possible. Customers of e.g. a mail-order business for fashion could examine the visual impression of clothing fitted to their avatars before ordering the goods.

In such scenarios realistic surfaces of objects – obtained by use of high resolution models and rendering techniques – are desirable. But the interactive aspect gains top priority. The immediate visualisation of changing parameters and movement of the figurine are therefore considered further goals which have to be achieved. So the compromise between real time behaviour and smooth surfaces [2] which must be made due to computer performance limits, however, occurs in favour of a quick reaction. Therefore, the description of any presentation improvements of the computed figurine beyond the wire frame model like texturing are only briefly addressed in Section 5.

2 State of the art

Many of the established or proven methods for modelling a figurine are not sufficient considering the criteria mentioned in Section 1.

Scanning of a person with a 3D scanner yields the most realistic model, due to the fact that the recorded data can be converted to 3D coordinates of the virtual model without further significant calculation. The suitability for practical use is proven by several companies which use the 3D complete body scan technique for manufacturing of tailor-made clothes [7]. Unfortunately the necessary equipment costs at least € 15,000 and is therefore unaffordable for the private user.

The calculation of a 3D model based on a series of photos taken from different angles with a digital camera, is another approach. Potentially this leads to results just as good as the scanning technique with less costs in comparison. UZR [12] Software already supplies a procedure for building 3D objects out of small physical objects like a foot or a head which must be located in front of a specified UZR template. Using this procedure to compute models with an acceptable quality, studio equipment and much training effort is required (see also Section 5).

Under the presumption of independence from special peripheral devices and equipment, the modification of pre-configured figurines in a 3D modeller such

[2] A detailed comparison of both aspects is given in [11].

like *3ds max* [5] or the specialised *Poser* [3] will provide the most accurate results, but only if the user possesses a considerable amount of know-how in three-dimensional design and is willing to invest a lot of time. Hence, this kind of software is not suitable for the intended purpose.

A recourse to traditional methods of the tailor's trade for manufacturing of made-to-measure clothing, i.e. taking of measurements, leads to the main concept. All criteria are met, if only a small amount of body measurements will be sufficient for the computer to build the virtual figurine in a reasonable amount of time: A ruler and a tape measure allow girths and lengths from the own body to be taken easily in a few minutes without assistance.

This idea is already used and has delievered acceptable results in some commercial programmes like *Runway* from OptiTex [9], where around fourty parameters for body measurements of a model are adjustable in real time. The proposed procedure, which will be discussed more detailed in the following, differenciates from the existent solutions in a way that a roughly adapted model can already be computed by solely using one ready-made clothes size. Furthermore the degree of accuracy of individualization increases successively, if more data are available to perform the calculation.

3 Determination of measurement data

3.1 Starting situation

This and the next section describe the modelling of figurines based on body measurements. Following the German Standard (DIN) for body measurement definitions [4], we have selected 36 representative measurements and put together as a set M. Apart from some generic information (see Section 5) these will be the only variable values that are needed to build the replica. Hence the criteria mentioned in Section 1 – usabilty and independence from non-conventional equipment – are already fulfilled. In order to achieve that the user only needs a small amount of time to enter the necessary data, only a subset M_m of these measurements should be made mandatory for input.

Special attention for the measurements in M_m was directed towards the possibility for pre-definition of ready-made sizes, thus resulting in a further reduction of user input time, and to the feature that a single person should be capable to take the required measurements by itself, which means that for M_m especially girths, body height and length of arms are important. The remaining measurements $M_{\neg m} = M \setminus M_m$ are assumed to be calculable by using an appropriate algorithm which uses additional inputs for the individual values of $M_{\neg m}$ for improving the accuracy of the adaptation.

3.2 Calculation of missing measurements

A first step towards the development of such an algorithm was the verification of various assumptions on how the measurements $m_j \in M_{\neg m}$ would depend upon the measurements $m_i \in M_m$. Verification of the assumptions ocurred by comparison with measurment data taken from the "Antropologic Atlas" [6] – a listing of nearly all seizable body measurement data with comprehensive statistic tables – and by evaluation of individual measurements taken from subjects following the procedures supplied by [6].

Non trivial assumptions like the attempt to calculate depth and width of waist, both in $M_{\neg m}$, from waist-line using an ellipse equation, produce sobering results: concurrences for one subject are accompanied by strong deviations for another. Similarly, this proved to be true when comparing the values for various age groups in [6]. The impact of many other factors apart from the measurements contained in M_m on those from $M_{\neg m}$ seems to be such that even sophisticated algorithms do not promise success. In fact, the simple equation

$$\begin{aligned} &\forall\, m_j \in M_{\neg m} : w(m_j) = a_{ij} \cdot w(h(m_j)), \\ &\quad h : M_{\neg m} \to M_m,\ h(m_j) := m_i \in M_m,\ a_{ij} \in \mathbb{R}, \end{aligned} \tag{1}$$

where w defines the actual value of a measurement, provides comparable or even better results when compared with more comprehensive functions based on M_m. For each $m_j \in M_{\neg m}$ the most influential measurement value can be found easily. The constants a_{ij} have been defined specifically for sex and age depending on the tables given in [6].

Having taken the values for all main body measurements in M_m all subordinated measurements in $M_{\neg m}$ can be calculated from equation (1). Furthermore, when extending the domain of h from $M_{\neg m}$ to M and setting $h(m_i) = m_i$ for all $m_i \in M_m$, an equivalence relation with classes $D(m_i)$ can be derived:

$$\begin{aligned} &D(m_i) = \{m_j \in M \mid h(m_i) = h(m_j)\},\ m_i \in M, \\ &\Longrightarrow M = \bigcup_{m_i \in M_m} D(m_i), \quad D(m_i) \cap D(m_j) = \emptyset \text{ for } m_i, m_j \in M_m. \end{aligned} \tag{2}$$

After input of the main measurements and calculation of the subordinated measurements, certain difficulties may occur when the user is enabled to manipulate any of the $m_i \in M$. All those measurements which have not been manipulated manually must be adapted skillfully afterwards. An adaptation algorithm which can be used for this purpose is described below.

In addition to the subdivisions of M described so far, further ones must be taken into account:

At first, M can be subdivided into "vertical measurements" M_v and "horizontal measurements" M_h. M_v contains all measurements taken along the bones of the skeleton. Two basically different measurement methods are possible to perform this: using overlapping lengths with a common reference point for body height axis and each extremity measurement (see "vertical measurements" in Fig. 1), for example waist and shoulder height measured against the ground or, secondly, using lenghts being complementary such like upper and lower arm lengths. The decision for the overlapping method – because of the more frequently occurrence in [4] – and the choice of the longest measurement per axis as the main measurement value result in a simple algorithm.

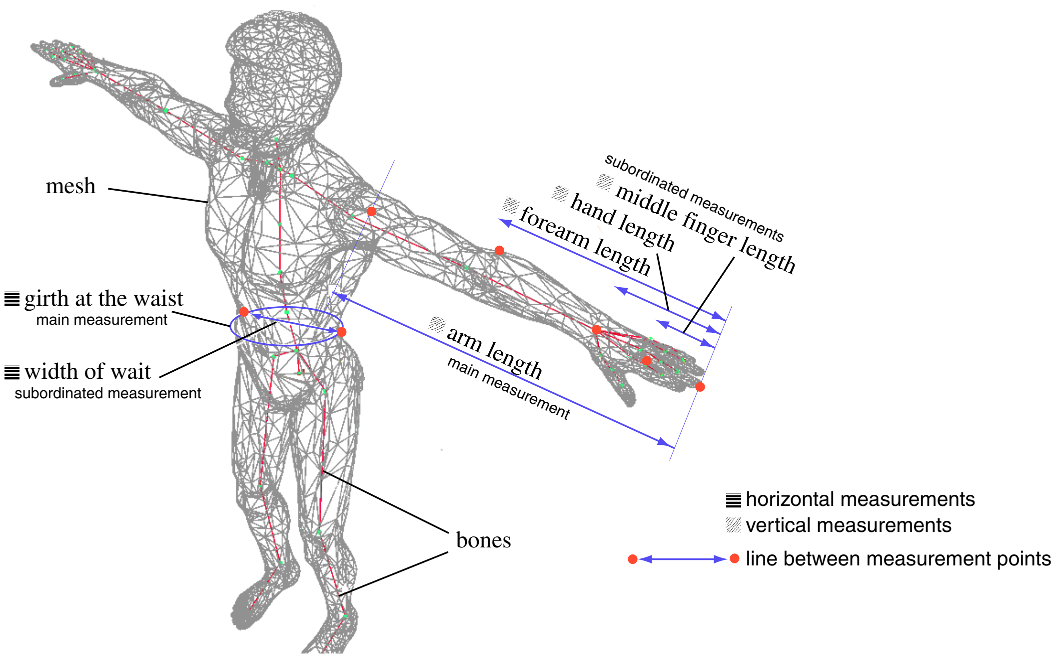

Fig. 1. "Vertical" and "horizontal" measurements with their assigned subordinated measurements

Finally M_h summarizes all other measurements, in detail: girth, depth and width measurements. When allocating the sub-measures to the main measures, it is important not to combine horizontal and vertical measures in one equivalence class: $\forall D(m_i) : D(m_i) \subset M_v \ \vee \ D(m_i) \subset M_h$.

Further, the measures must be subdivided into fixed and modifiable ones by means of $\chi : M \rightarrow \{c, \neg c\}$. All measures, where a value was allocated by the user, are fixed. This normally includes all main measures.

One by one the equivalence classes $D(m_i)$, each of them represented by exactly one $m_i \in M_m$, $1 \leq i \leq \#M_m$, are changed according to the properties of their elements.

3.3.1 Horizontal measurements

If $D(m_i) \subset M_h$, then four cases have to be differentiated:

(1) $\forall\, m_j \in D(m_i) \setminus \{m_i\} : \chi(m_j) = \neg c$.
The values of all modifiable subordinated measurements in $D(m_i)$ can be calculated from m_i using equation (1).

(2) $\chi(m_i) = \neg c \ \wedge \ \exists\, m_1, \ldots, m_k \in D(m_i) \setminus \{m_i\} : \chi(m_1) = \ldots = \chi(m_k) = c$.
In this case the value of m_i can be calculated as an average of the k fixed sub-measurements, for example as the geometric mean: $w(m_i) = \sqrt[k]{\prod_{j=1}^{k} \frac{w(m_k)}{a_{ij}}}$. The values of the modifiable sub-measurements in $D(m_i)$ can be found using equation (1).

(3) $\chi(m_i) = c \ \wedge \ \exists!\, m_j \in D(m_i) \setminus \{m_i\} : \chi(m_j) = c$.
If the input value of m_j is larger than the the supposed value $a_{ij} \cdot w(m_i)$, the values of the other subordinated measurements, especially if perpendicular to m_j, must be reduced. If contrariwise $w(m_j)$ is smaller than $a_{ij} \cdot w(m_i)$, the other values have to be extended.The reason is, that in this way an approximately elliptical shape of girth is preserved.

This correction can be implemented by multiplication with $\Delta a_{ij} = \frac{a_{ij} \cdot w(m_i)}{w(m_j)}$. The influence of Δa_{ij} is proportionally dependant on the smallest angle α between the measurement lines of fixed and modifiable measurements:

$$\begin{aligned} &\forall m_k \in D(m_i) \setminus \{m_i, m_j\} : \\ &\quad w(m_k) = a_{ik} \cdot (\sin^2 \alpha \cdot \Delta a_{ij} + \cos^2 \alpha) \cdot w(m_i). \end{aligned} \tag{3}$$

α must be determined in advance, e.g. by means of a table containing the angle sums of all subordinated measurements per class. The case of more than one subordinated fixed measurement should be forbidden due to consistency matters, as illustrated in 4.2.4.

3.3.2 Vertical measurements

For $D(m_i) \subset M_v$ we propose the following procedure.

If $\chi(m_i) = \neg c$, then m_i must be set fixed first: If $\forall\, m_j \in D(m_i) \setminus m_i : \chi(m_j) = \neg c$, this can easily be done, otherwise a more precise value for m_i should be calculated from the value of the longest fixed subordinated measurement m_k: $w(m_i) = \frac{w(m_k)}{a_{ik}}$. This ensures the exclusion of inconsistencies like $w(m_i) < w(m_j)$ for $m_j \in D(m_i)$.

The class $D(m_i)$, containing n measurements, has to be augmented by an element $m_{n+1/i}$ with $\chi(m_{n+1/i}) := c$ and $a_{i(n+1)} := 0$. Thereupon the elements $m_{j/i}$ in the resulting set $D(m_i) \cup \{m_{n+1/i}\}$ must be indexed in a way that their coefficients a_{ij} are in descending order ($a_{ik} < a_{ij}$ for $1 \le j < k \le n+1$), i.e. the differences of the coefficients of successive measurements are defined by

$$\Delta a_{ij} := a_{ij} - a_{i(j+1)} \geq 0. \tag{4}$$

$m_{1/i} = m_i$ per pre-condition. Therefore $m_{1/i}$ is fixed. According to equation (1) $a_{ii} = 1$. Because $m_{n+1/i}$ is also fixed, every modifiable measurement m_j is embedded within at least two fixed measurements: $1 \le k < j < l \le n+1$ for fixed measurements $m_{k/i}$, $m_{l/i}$. Hence its value can be calculated as follows:

The differences of the values of successive measurements $\Delta w_{j/i} := w(m_{j/i}) - w(m_{j+1/i})$ correspond to the differences of the closest surrounding fixed measurements $w(m_{k/i}) - w(m_{l/i})$ like the associated differences of their coefficients:

$$\frac{\Delta w_{j/i}}{w(m_{k/i}) - w(m_{l/i})} = \frac{\Delta a_{ij}}{a_{ik} - a_{il}}. \tag{5}$$

For a detailled derivation of this equation see App. A. After calculation of all $\Delta w_{j/i}$ with equation (5) the value of a modifiable subordinated measurement is given by

$$w(m_{j/i}) = w(m_{l/i}) + \sum_{z=j}^{l-1} \Delta w_{z/i} \tag{6}$$

The algorithm above only succeeds if the provided order conditions are met by the input values. Therefore it is reasonable to allow user data input only, if it fulfills a certain set of rules, e.g.

$$\{\text{body height} > \text{shoulder height},\ \text{chest width} \leq \frac{1}{2} \cdot \text{chest girth}, \ldots\}.$$

4 Computation of the figurine

The measurement values, entered or calculated as shown in Section 3, must be transfered to the base model of a 3D figurine in such a way that distance and girth values, determined from the skeleton and certain points of the model (in the following: vertices, tripel consisting of x, y and z coordinates), will coincide with the corresponding measurement data, while the figurine as such remains recognisable. That means the vertices outside of specifically manipulated point areas (those coupled to a measurement) must be adapted with respect to their coordinates in a way that a natural shaping of the figurine is preserved.

4.1 Vertical measurements

The transfer of all measurements m_{vj} in M_v to the virtual figurine is a rather simple task, because it is supported by the construction of the 3D model: the vertices are located at positions relative to certain virtual bones s_i taken from the skeleton S (see 4.2.1). Any modification of the bone length will proportionately affect those vertices attached to the bone: limb measurements of the figurine are compressed or extended, without degrading the naturalness of the shape – to a certain extent, of course.

To proceed, merely a map has to be built that allocates a length measurement to each bone s_i. The measurement is composed of multiples of differences taken from the available measurement values $w(m_{vj})$. For example, the virtual thigh bone is defined as

$$\text{(crotch height} - \text{knee height)} + 0.7 \cdot \text{(iliac bone height} - \text{crotch height)}.$$

Equation (7) enables to calculate the bone length in general:

$$\text{len} : S \to \mathbb{R},\ \text{len}(s_i) = \sum_{j<k} a_{sjk} \left(w(m_{vk}) - w(m_{vj}) \right), \tag{7}$$

where $m_{vj} \in M_v \cup \{m_{v0}\}, \quad w(m_{v0}) = 0, \quad 1 \leq j,k \leq \#M_v$. It is sufficient to define only a few $a_{sjk} \in \mathbb{R}$ in advance, for example by adjustment of measurement points on the real person and the start coordinates of bones in the figurine, and setting all other a_{sjk} to zero.

The adaptation of the figurine to horizontal measurements requires much more effort. The proposed procedure described below deals with at least two model variants of the same figurine which should differ as much as possible regarding measurement values, e.g. a thick and a thin base model. Between those the computed model will be located. This method reduces the input range for the m_{hi} in M_h, but as intended it protects against degenerated results.

4.2.1 Definitions

First of all, the structure of the figurine and auxiliary constructions used for the adaptation procedure must be considered:

A figurine consists of an anchor point which defines its position in space, a skeleton S as well as a base mesh and in addition, one or more so-called morph meshes. The skeleton S represents a tree structure of single bones s_i. Every s_i is defined by a reference to its parent bone (for the bones of the first hierarchy level: the anchor point) and a direction vector $v_r(s_i)$ with $|v_r(s_i)| = \text{len}(s_i)$. By means of traversing the tree the start and end coordinates $\text{start}(s_i)$, $\text{end}(s_i) \in \mathbb{R}^3$ can be calculated.

4.2.1.1 Meshes A mesh is assumed to be a sequence of vertices $V = (v_1, \ldots, v_n)$ which occur as triples, forming triangles in space, describing the surface of the figurine, whereas the belonging of a vertex to a certain triangle group is irrelevant for the adaptation procedure.

The base mesh V_g consists of weighted vertices; that means for each vertex the function $\text{coeff}_v : S \to \mathbb{R}$ maps coefficients to one or more bones that indicate how the vertex will be moved if the position of the bone changes. The coefficients represent spheres of influence around bones which are already defined during the building of one of the base models and are actually forseen for the natural appearance of animations [1, 8]. Usage of these coefficients is made in body areas (see below).

A morph mesh $V_m = (v'_1, \ldots, v'_n)$ represents a modified body shape derived from the base mesh, for instance a thin or corpulent shape. Essentially V_m corresponds to V_g, with the exception that the v'_i in comparision to the v_i may have deviating coordinates, due to the modified shape. The weightings are the same as in V_g. Thus, in particular V_g represents a morph mesh.

4.2.1.2 Planes As an auxiliary construction for mesh adaptation a set E of special planes e_i is used. Each plane is located orthogonally to a bone and intersects with it at a height which corresponds to the height where the measurement is taken on the real figurine (Fig. 2).

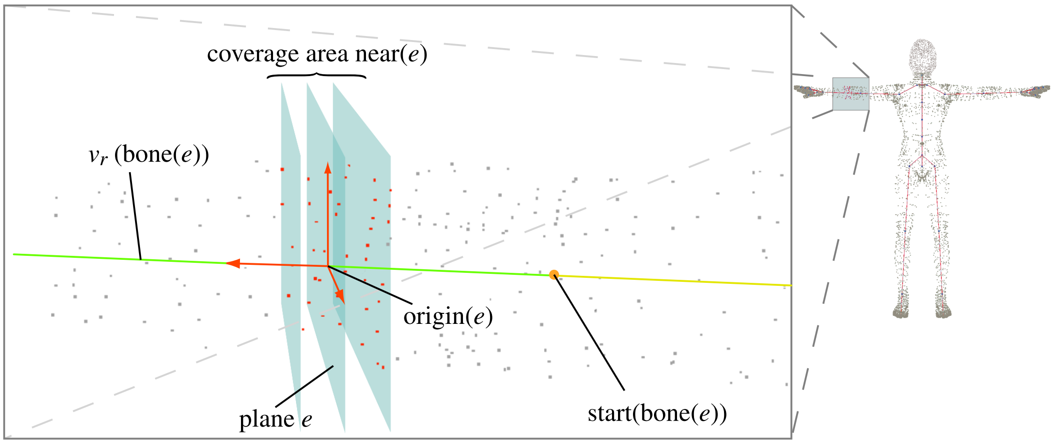

Fig. 2. Construction of a plane

Every measurement from M_h, if it is to be used, must be allocated to a plane. The characterisation of e_i (see Fig. 2) comprises a bone, defined by $\text{bone}(e_i) \in S$, an intersection value $0 \leq \text{cut}(e_i) \leq 1$, which identifies the point of intersection relative to $v_r(\text{bone}(e_i))$, and $M_{e_i} \subset M_h$. To preserve consistancy (see 4.2.4), M_{ei} is allowed to contain either a girth measurement, additionally a width or depth measurement or only two length values. Accordingly, E can be divided into E_u, E_{ul} and E_l.

Furthermore, there exists a value $\text{near}(e_i)$ and an orthonormal basis change matrix: $\text{basis}(e_i) \in M_3(\mathbb{R})$. The former describes a coverage area, the latter serves to convert standard basis coordinates of a vertex into the coordinates of a plane basis B_{e_i}, which is constructed from the normalized $v_r(\text{bone}(e_i))$ and two vectors in the plane, with their origins lying in the intersection with $\text{bone}(e_i)$, defined by

$$\text{origin}(e_i) := \text{start}(\text{bone}(e_i)) + \text{cut}(e_i) \cdot v_r(\text{bone}(e_i)). \tag{8}$$

Thus the standard coordinates of a vertex can be converted into coordinates of the plane by using the mapping

$$k_{e_i} : V \to V, \quad v \mapsto \text{basis}(e_i) \cdot (v - \text{origin}(e_i)) \tag{9}$$

Conveniently, the first coordinate $(k_{e_i}(v))_1$ always specifies the distance to e_i, and if $(k_{e_i}(v))_1$ is set to zero, a projection $p_i(v)$ onto the plane is gained.

Optionally, a so-called tag or orientation vector $v_T(e_i)$ can be linked to e_i. It is necessary to find pairs of vertices, whose distances coincide with measured width and depth values.

4.2.1.3 Body areas A body area b_i is defined by one or several bones $S_{b_i} \subset S$ and one or two planes $E_{b_i} \subset E$. The set V_{b_i} of all vertices belonging to b_i [3] is concluded through the equation

$$V_{b_i} = \{v \in V_g \mid \exists s_i \in S_{b_i} : \mathrm{coeff}_v(s_i) \neq 0 \\ \text{and} \left. \begin{array}{ll} v \text{ lies between } e_1 \text{ and } e_2, & \text{if } E_{b_i} = \{e_1, e_2\} \\ (k_{e_1}(v))_1 > 0, & \text{if } E_{b_i} = \{e_1\} \end{array} \right\} . \tag{10}$$

There are two aspects that lead to the second condition in equation (10):
(1) Body areas with a single plane are only intended for outer areas of limbs.
(2) According to construction, directional vectors of planes always point outwards.

Whether v is positioned between two planes is either given by v lying on e_1 or e_2, that means $p_j(v) = v \iff (k_{e_j}(v))_1 = 0$, $j \in \{1, 2\}$, or can be derived from the angle α of the perpendiculars $\lambda_{v1} \neq 0$ and $\lambda_{v2} \neq 0$ of v onto the planes:

$$\lambda_{vj} = \mathrm{basis}^{-1}(e_j) \cdot \Big((k_{e_j}(v))_1, 0, 0\Big), \quad j \in \{1, 2\} \tag{11}$$

If $\alpha = \dfrac{\lambda_{v1} \cdot \lambda_{v2}}{|\lambda_{v1}||\lambda_{v2}|}$ is less than $\frac{\pi}{2}$, both planes are positioned on the “same side” of v.

4.2.2 Convex hulls

As a first step it is necessary to define for each plane a corresponding set $V_{g/\mathrm{near}(e_i)} \subset V_g$ consisting of nearby vertices:

$$V_{g/\mathrm{near}(e_i)} = \{v \in V_g : |(k_{e_i}(v))_1| \leq \mathrm{near}(e_i) \ \wedge \ \mathrm{coeff}_v(\mathrm{bone}(e_i)) \neq 0\}. \tag{12}$$

A convex hull $V_{g/i}$ of projections $p_i(v)$ of $v \in V_{g/\mathrm{near}(e_i)}$ onto e_i regarding B_i (see 4.2.1.2) yields values for girth, depth and width measurements of the virtual figurine in height of the plane. To be as precise as possible the value of $\mathrm{near}(e_i)$ must be high enough not to allow $\#V_{g/i}$ to get too small, and low enough to

[3] As an alternative to the division of V_g according to vertex weightings, V_{b_i} can also be defined as a union of several submeshes, i.e. subdivisions of V_g carried out beforehand.

guarantee that vertices far away from e_i do not contort the shape. The higher the vertex density of the base mesh, the lower near(e_i) can be chosen.

The order of the elements in a convex hull, if constructed with standard algorithms, is immediately used for the calculation of the hull's girth as sum of the differences of sequential elements:

$$\text{girth}(V_{g/i}) := v_1 - v_{\#V_{g/i}} + \sum_{k=1}^{\#V_{g/i}} (v_{k+1} - v_k) \tag{13}$$

Furthermore a tag $v_T(e_i)$, used as a transposition from the origin of the plane, defines a zero mark for the angle. With $v_T(e_i)$ vertices v_{b1}, v_{b2}, v_{t1}, v_{t2} from $V_{g/i}$ can be found, whose absolute values of their differences $|v_{b1} - v_{b2}|$, $|v_{t1} - v_{t2}|$ each correspond to a width or depth measurement.

Let the angles of the tag $v_T(e_i)$ to the measurement lines of length measurements be pre-set in every plane e_i containing lengths, e.g. 0 for widths, $\frac{\pi}{2}$ for depths, then v_{b1} and v_{b2} can be identified as those vertices opposing the origin of the plane, whose connecting line, projected onto e_i, forms the smallest possible angle to $v_T(e_i)$:

$$\forall\, w \in V_{g/i} : \frac{v_{b1} \cdot v_T(e_i)}{|v_{b1}||v_T(e_i)|} \leq \frac{w \cdot v_T(e_i)}{|w||v_T(e_i)|} \;\wedge\; \frac{v_{b2} \cdot v_T(e_i)}{|v_{b2}||v_T(e_i)|} \geq \frac{w \cdot v_T(e_i)}{|w||v_T(e_i)|}. \tag{14}$$

v_{t1} and v_{t2} can be acquired accordingly.

4.2.3 Mesh selection

Thus in each of the different meshes all measurements of the virtual figurine that coincide to the measurements $m_h \in M_h$ can be calculated. To create a new mesh, where the values for the horizontal measurements correspond to those in M_h, an approach would be to detect for each body area b_k those two meshes $V_{\underline{m}}$ and $V_{\overline{m}}$, which enclose M_h the most. For $m_{hi} \in M_{e_i}$, $e_i \in E_{b_k}$ only the following two equations must be fulfilled, whereas $\underline{w}$, $\overline{w}$ and w' are value mappings belonging to $V_{\underline{m}}$, $V_{\overline{m}}$ respectively to a further mesh $V_{m'}$ and $m_{hj} \in M_{e_j},\ e_j \in E_{b_k}$.

$$\underline{w}(m_{hi}) \leq w(m_{hi}) \leq \overline{w}(m_{hi}) \tag{15}$$

$$\begin{aligned} \forall\, V_{m'} : \underline{w}(m_{hi}) \leq w'(m_{hi}) \leq w(m_{hi})\ \exists\, m_{hj} :\ w(m_{hj}) < w'(m_{hj}) \\ \text{and}\ \forall\, V_{m'} : w(m_{hi}) \leq w'(m_{hi}) \leq \overline{w}(m_{hi})\ \exists\, m_{hj} :\ w'(m_{hj}) < w(m_{hj}) \end{aligned} \tag{16}$$

Thereby the necessary changes of body shapes will be kept as small as possible. Unfortunately until now this approach fails due to the problematic realisation of smooth transitions between adjacent body areas. Nevertheless it can be used reasonably, if the measurements are not considered plane by plane but alltogether, therefore $m_{hi} \in M_h$ instead of $m_{hi} \in M_{e_i}$.

4.2.4 New convex hulls

Now each plane e_i causes hulls $V_{\underline{m}/i}$ and $V_{\overline{m}/i}$ in $V_{\underline{m}}$ and $V_{\overline{m}}$ respectively. Based on them a new hull $V_{m/i}$ with the following characteristics is ascertainable:

- $$\begin{aligned} &\forall v \in V_{m/i} : v = \underline{v} + r_v \cdot (\overline{v} - \underline{v}) \\ &\underline{v} \in V_{\underline{m}/i},\ \overline{v} \in V_{\overline{m}/i},\ r_v \in \mathbb{R},\ 0 \leq r_v \leq 1 \end{aligned} \tag{17}$$

  Of course, v, $\underline{v}$ and $\overline{v}$ must coincide in their indices, determined during mesh construction.
- All values for $m_{hi} \in M_{e_i}$, calculated with $V_{m/i}$, match those $w(m_{hi})$ determined in Section 3.

Hence – as considered before – the measurement data have to be checked against those conditions [4] already during input. The next section deals with that topic in detail.

If e_i is in the equivalence class E_u, it is sufficient to determine one r for all $v \in V_{m/i}$ by adapting the only measurement m_u in M_{e_i}, the girth of $V_{m/i}$, to the input $w(m_u)$. As a side-effect a single coefficient provides an optimal interpolation of $V_{\underline{m}/i}$ and $V_{\overline{m}/i}$. The adaptation of girth($V_{m/i}$) occurs, starting with $r = 0$, due to repeated changes of r and the subsequent determination of girth($V_{m/i}$). The value of r is increased as long as girth($V_{m/i}$) $< w(m_u)$, and vice versa. Per successive decrease of the distance of steps $w(m_u)$ can be approached to an arbitrary distance. In consequence of data verifications (see 4.2.5) girth($V_{\underline{m}/i}$) and girth($V_{\overline{m}/i}$) cannot be exceeded. Thus – according to equation (17) – r remains between 0 and 1.

If $e_i \in E_l$ and $m_l \in M_{e_i}$ is a width measurement, a common coefficent r can be stated directly. Are $v_{b1}, v_{b2} \in V_{\underline{m}/i}$, $v'_{b1}, v'_{b2} \in V_{\overline{m}/i}$, determined as described in 4.2.2, then $|v'_{b2} - v'_{b1}| \geq d := |v_{b2} - v_{b1}|$ and $\Delta d = \frac{1}{2}(w(m_l) - d)$, so that

$$r = \frac{1}{2}\left(\frac{\Delta d}{|v'_{b1} - v_{b1}|} + \frac{\Delta d}{|v'_{b2} - v_{b2}|}\right) = \frac{1}{4}\left(\frac{w(m_l) - d}{|v'_{b1} - v_{b1}|} + \frac{w(m_l) - d}{|v'_{b2} - v_{b2}|}\right) \tag{18}$$

[4] One could allow $r < 0$ or $r > 1$, but this would result in a strong deviation of the figurine and in collisions of body areas, even if the interval $[0, 1]$ is only slightly exceeded.

The equation is illustrated by Fig. 3. The procedure for depth measurements is the same.

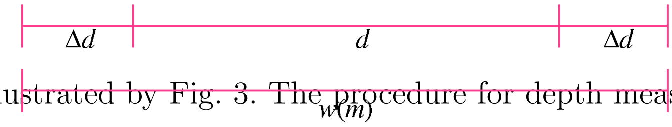

Fig. 3. Minimal, maximal and desired lengths in relation

If e_i belongs to E_{ul}, i.e. $M_{e_i} = \{m_u, m_l\}$ with girth and length measurements m_u and m_l, there are already two values $r_l,\ r_u$ required, with which the coefficient for every vertex $v \in V_{m/i}$ is calculated individually via

$$r_v = r_l + r_u \cdot \sin\alpha, \quad r_l,\, r_u \in \mathbb{R},\ 0 \leq (r_l + r_u) \leq 1,\ \alpha = \frac{k_{e_i}(v) \cdot d}{|k_{e_i}(v)||d|}, \tag{19}$$

whereas $d = v_{b2} - v_{b1}$, if a width measurement is present (see above), and $d = v_{t2} - v_{t1}$, if m_l is a depth measurement.

The equation can be explained as follows: first, like in the case of $e_j \in E_l$, the convex hull $V_{\underline{m}/i}$ is increased to the desired size $w(m_l)$ and thus r_l is determined. Then the points v of this hull are moved according to the angle of $k_{e_i}(v)$ and d until girth$(V_{m/i})$ is in the pre-set neighbourhood of $w(m_u)$. The procedure is akin to the girth approximation for planes in E_u, but the points have to be moved maximally if they are orthogonal to d and only little if the points are close to d, to preserve the correspondence to $w(m_l)$.

One could imagine the case of a plane e_k with two length measurements in M_{e_k}, which is not dealt with seperatly because of the little gain of information in comparison to E_{ul}, but could be described as a combination of both cases mentioned above.

Furthermore it is noticable that more than two measurements per plane e_i will lead to inconsistencies (girth and width are predetermining the depth), if the shape between $V_{\underline{m}/i}$ and $V_{\overline{m}/i}$ is kept. A conversion of three measurements into the convex hull would not only require more complex methods, but would also mean to loose the advantage of shape keeping for many combinations of values.

4.2.5 Verification of user input

In most cases the verification of the input values is done by comparing them to the minimal and maximal girths and lengths of the convex hulls, which were calculated beforehand taking all morph meshes into account. For measurements assigned to planes in E_{ul} this is not always sufficient: If both the girth as well as a length in the same plane were set fixed, nevertheless some r_v may exceed the interval $[0, 1]$, because, for preserving girth *and* width or depth respectively, deviation of the ideal form, given by the meshes, is necessary (see Fig. 4).

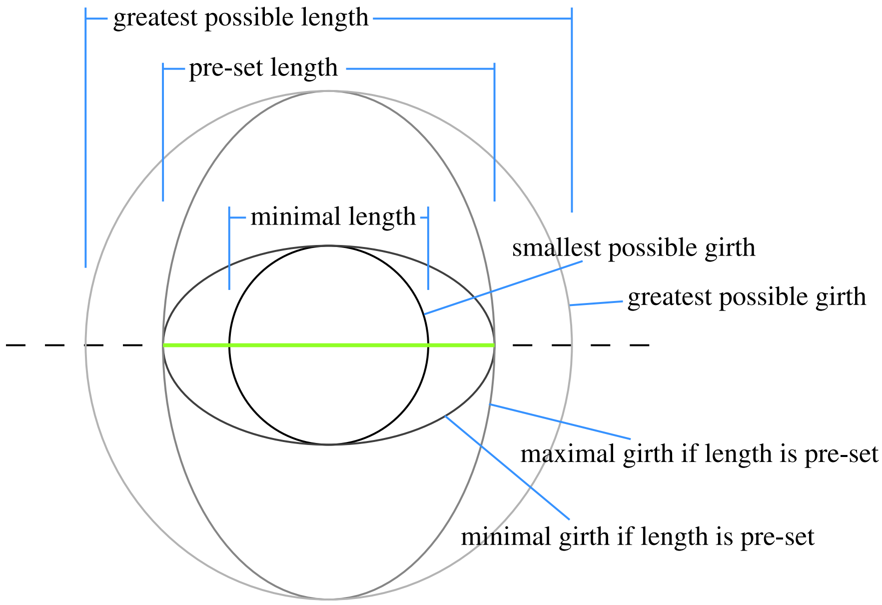

Fig. 4. Limitation of the input area for the girth while length is fixed

To guarantee $0 \leq r \leq 1$, first it has to be verified, whether the input length $w(m_l)$ does not fall below the minimal or exceed the maximal length, thereupon calculated r_l and tested, whether the input girth lies between two new values for the minimal and maximal girth, $\text{girth}^l_{min}(e_i)$ and $\text{girth}^l_{max}(e_i)$, depending on r_l. The corresponding convex hulls are depicted as ellipses in Fig. 4. The values r_v required for their calculation be means of equation (17) with α as defined in equation (19), arise from the diagram:

$$\begin{aligned} \text{girth}^l_{min}(e_i) &: r_v = r_l - r_l \cdot \sin\alpha \\ \text{girth}^l_{max}(e_i) &: r_v = r_l + (1 - r_l) \cdot \sin\alpha. \end{aligned} \tag{20}$$

Usage of equation (13) onto these hulls finally yields the new girth boundaries.

4.2.6 An adapted mesh

The construction of a mesh with a natural form, which is adjusted to all horizontal measurements, is realised with the help of the body areas: Every vertex $v \in V_{\underline{m}}$ lies in one, or at most two body areas (see 4.2.1.3). The latter is a rare special case, because $v \in V_{b_i} \cap V_{b_j},\ i \neq j \iff v = p_k(v) \wedge e_k \in E_{b_i} \cap E_{b_j}$. Therefore the consideration of only one area b_v is enough.

The position of v is moved to the position of $v' \in V_{\overline{m}}$ according to equation (17). Here r_v is a combination of r_{v1} and r_{v2}, the coefficients of the projections $p_j(v)$ of v onto the up to two planes[5] e_1 and e_2 in E_{b_v} under section 4.2.4. So if $e_1 \in E_u \cup E_l$ for example, r_{1v} corresponds to r, the coefficient common to all point in the plane.

The closer v and $e_j,\ j \in \{1, 2\}$, the stronger the influence of r_{jv} on r_v:

$$r_v = (1 - q) \cdot r_{v1} + q \cdot r_{v2}, \quad q = \frac{|k_{e_1}(v))_1|}{|k_{e_1}(v))_1| + |k_{e_2}(v))_1|} \tag{21}$$

5 Improving recognizability

The transfer of a person's body shape to a 3D model is not sufficient to ensure recognizability. Regarding this the following important aspects have to be considered:

Up to this point the look of the skin, gender, age classes as well as the physique in general and the characteristic of muscles or fat pads in particular were not considered yet. The former can be realised using different skin textures. The other aspects demand extras like the construction of morph-mesh-groups representing combinations of additional user input data (e.g. male, middle aged, athletic) with a following update of the mesh-pool.

Nevertheless recognizability can be fulfilled only to a low degree if no emphasis is put on face modelling. There are approaches to transfer the shape and colour of a face, a person's skin and eyes to a model that promise to meet the criteria of a quick but equipment independent data input, as outlined in 3.1. Examples are the construction of a 3D model of a head on the basis of a series of photos taken from different angles and the reshaping of a generic model through iteration using a single photo.

For the procedure mentioned first UZR [12] is a viable solution (see also Section 2). But good lighting, a non-reflecting background and manual post-editing of

[5] If b_v contains only one plane, set $r_{2v} = 0$

the border between head and background for each of the at least ten photos are preconditions for an acceptable quality. In addition a size adjustment of the head for the export into the virtual model has to be performed. The lacking automatisation of the data input operation is therefore the main disadvantage of this approach.

The second procedure, developed at the Max Planck institute for biological cybernetics, uses an average model of a head calculated from hundreds of 3D scanned heads with variance values belonging to points in a 3D grid, as well as a front image and in order to get better results an additional profile photo of the head to be modelled. Modelling itself is done by bringing step by step color values of the projection of the model into line with those in the photos, until an energy value resulting from the variances reaches its minimum. A detailed description and promising results can be found in [2]. The main problem with the practical use of this approach is the exclusion of hair.

The animation of the figurine and the possibility of dressing it are rather supportive characteristics for recognition, but a substantial benefit in concrete applications, as described in Section 1.

Using the popular technique of *skeletal animation* we were capable to supply the figurine with multitudous animations. Information about changes of bone positions (as described in 4.2.1) according to elapsed time is used to animate any vertex-object, in which the corresponding skeleton is integrated.

A realistic simulation of clothing, especially its behaviour under force effects, is a far more complex task. The mapping of colour and structure of clothing onto a figurine is no more than a first step: Only skin-tight clothes could be displayed convincingly. Natural movement of fabrics with knits and folds require procedures like the particle system, whose concept is explained in App. B, which is based on [10].

6 Conclusion

With the help of Fig. 5 the mesh, which was computed in a way as explained above, can be compared with the minimal and maximal mesh of the same figurine. Those pictures show the possible variation of several measurements. Table 1 lists the corresponding measurement values. In the pictures the preservation of realistic body proportions can be recognised. Since for a representation of the basic principles modelling of a few body areas is sufficient, at some parts of the figurine little or no changes are evident. If the base meshes were constructed with an appropriate expenditure, a significant increase of all ranges could be achieved.

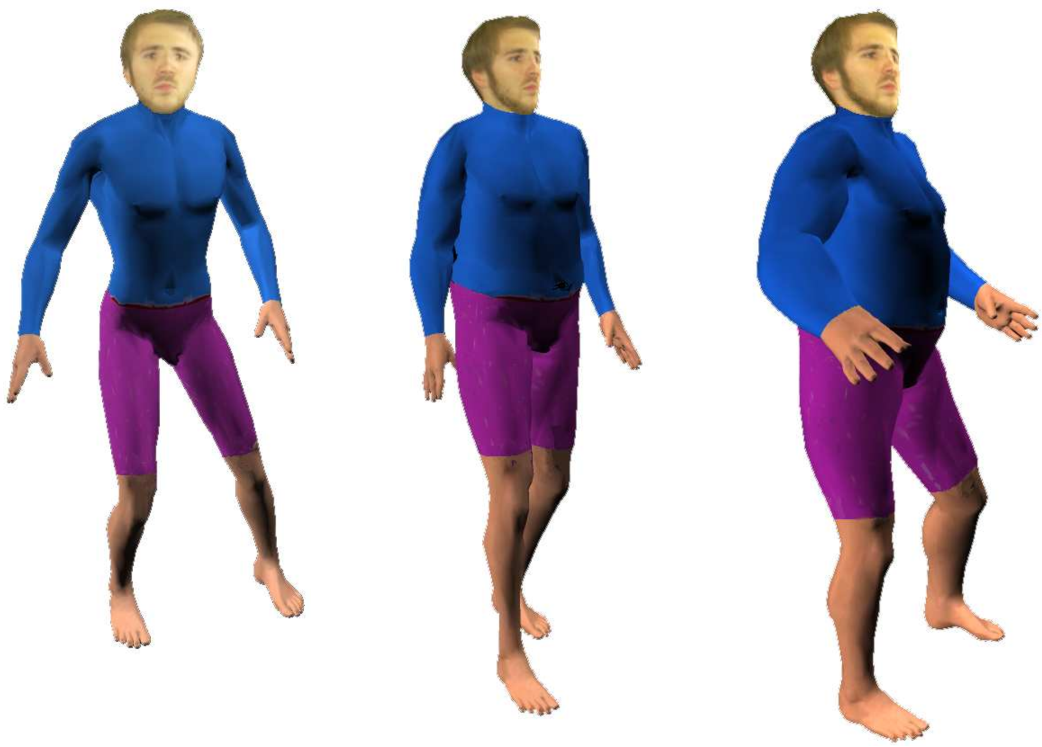

Fig. 5. minimal, adapted and maximized mesh

Table 1
measurement values for Fig. 5

measurement (cm)	minimal mesh	adapted mesh	maximal mesh
chest girth	98	110	119
thorax girth	90	102	115
waist girth	87	105	125
upper arm girth	35	43	50
wrist girth	19	22	31
thigh girth	51	61	70

Table 2 relates input measurement values to those values that are calculated from a selection of the input values (marked bold). The deviation from the calculated value to the input values can be traced back to the rigid calculation rules. It could be reduced, as mentioned in Section 5, by a subdivision into types like athletic, thickset etc. This could also include a different set of bones for each type, to enable the figurine to look even more realistic.

The computation time for the computation of an individualised figurine is about a second on a gigahertz computer and a mesh of 10.000 vertices. But

Table 2
Determinated data

measurement (cm)	entered value	calculated value
body height	**182**	
waist height	107	109
knee height	52	49
chest girth	**88**	
chest depth	22	20
arm length	**76**	
forearm length	45	46
hand length	18	19
thigh girth	**54**	
shank girth	36	35

since there have been done only a few attempts to optimize the procedure regarding the calculations or the reuseability of unchanged data, an almost realtime behaviour seems to be achievable.

There is however no shortage of possible basic improvements for the described procedure. For example, due to the special demands on the meshs (same number of vertices, V_g pre-sets the sequence of positions) up to now, the number of available different meshes can only be increased manually and very slowly. A solution to this problem could be correspondence analysis, which means that from two morph meshes of nearly arbitrary descent each, vertex-couples are determined automatically, e.g. by search for similar vertex coordinates or colour values, and ordered according to V_g. Correspondence analysis would be very helpful to extend the mesh pool more quickly and thus to increases the resemblance of the computed figurine to the real person. Just to mention another example: the raise of the number of measurements and planes used for adaption would probably have an effect of equal value.

However we deem the described procedure for modelling a figurine using body measurement to be a promising start and well worth for further development.

A Derivation of equation (5)

The quotients of the fixed measurements $m_{k/i}$, $m_{l/i}$ and m_i are already determined by user input. From the difference $\Delta p_{kl} = \frac{w(m_{k/i})-w(m_{l/i})}{w(m_i)}$ of these quotients the Δa_{ij} of the variable measurements in between can be recalculated:

$$\Delta a^*_{ij} = \frac{\Delta p_{kl} \cdot \Delta a_{ij}}{a_{ik} - a_{il}} = \frac{\frac{w(m_{k/i}) - w(m_{l/i})}{w(m_i)} \cdot \Delta a_{ij}}{a_{ik} - a_{il}} \tag{A.1}$$

The corresponding corrected value differences of these variable measurements are derived from them by

$$\begin{aligned} \Delta w_{j/i} = \Delta a^*_{ij} \cdot w(m_i) &= \frac{(w(m_{k/i}) - w(m_{l/i})) \cdot \Delta a_{ij}}{w(m_i) \cdot (a_{ik} - a_{il})} \cdot w(m_i) \\ &= \frac{w(m_{k/i}) - w(m_{l/i})}{a_{ik} - a_{il}} \cdot \Delta a_{ij}. \end{aligned} \tag{A.2}$$

This yields equation (5).

B Particle systems

Particle systems are based on the theory of cellular automata, where the state of a particle at a certain timestep $t + 1$ is influenced by the states of its neighbours at timestep t.

Thus to simulate textiles it is necessary to regard a woven piece of cloth as a two-dimensional set of particles, each of which is connected to its direct neighbours. During the steps of calculation every particle tries to gain a more ideal position with respect to the positions of its neighbours.

To calculate the new position three parameters will be required: elasticity, shearing and bending forces. Elasticity defines the maxium offset of a particle to its neighbour. If this offset is exceeded, both particles try to move closer towards each other.

Shearing defines the angle between a particle and two of its adjacent particles. In case the angle exceeds a certain degree the neighbours will move towards each other. Finally bending defines the allowed deviation of a particle from a line built up by two opposing neighbours. If the deviation becomes too large, the particle moves towards the centre of the line defined by the neighbours.

In order to achieve a realistic drape by this means, it is necessary to start with an unbent piece of cloth, where all particles lie in one single plane and are affected by a force, e.g. gravity. As soon as an obstacle is hit while moving downwards, for instance the body of a figurine, certain particles are no more capable of moving and tensions with their neighbours arise.

Because in every step of calculation the three described parameters are included for the calculation of each particle of the cloth, tensions will be somewhat counteracted. After a finite number of calculation steps a final state will be reached, which accords with a real textile regarding appearance and arrangement of the folds.

A more detailed discussion regarding particle systems provides [10].

C Working group members

Nils Behrens, Bahir Bilgin, Sylvia Bluhm, Derya Bozkurt, Wilfried Grabbe, Christian Kluin, Alexander Köhn, Gerhard Kost, Siegfried Kramer, Alparslan Kuzu, Magda Mazurek, Sebastian Meister, Cemal Öncel, Joachim Penk, Claas Potthoff, Harry Rechten, Martin Spreckelmeyer, Vincent Stickdorn, Mehmet Ünal, Alexander Washausen, Florian Weiler, Tobias Wüst

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