Article

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Reference

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Keywords Anthropometry · Deformation · Human body · Skeleton

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1 Introduction

In Computer Graphics (CG), there has been a keen interest in the study of human body design and modeling. With the significant hardware and software developments in CG, stick-like characters are superseded by more realistic 3D ones. This progression is mostly focused on achieving realism in virtual environments (VEs) to improve the visual perception. Depending on the functionality of each element in VEs, efficient shading, skinning, and motion algorithms are developed to simulate their physical properties. Most of these techniques are focused on human body models, which are very important elements of these environments.

The animation of these static human body models is also another research field that requires additional skinning and motion data. Mainly the virtual character animation technology uses the linear blend skinning (LBS) method [12] which is a very efficient and convenient method for real-time applications. To animate a model, first a virtual template skeleton is attached on the mesh and the model surface is deformed along with the skeleton's motion. Generally, the Humanoid animation (H-Anim) standard is used to enable shared animations on the virtual human character. Rigging this virtual character increases the perception of realism in the human mind.

Due to a number of limiting factors, VEs are depicted with several instances of a fixed number of template body models to improve the visual realism. Generally, varieties of textures are mapped or motions are attached on each instance to achieve the visual variance [13]. Even with different textures, similarity between these fixed size template models can easily be noticed.

Using a skinned template body model, we developed a method to automatically segment it into anatomical regions and size it within an anthropometric measurement standard.

By this way, we achieve a size variance in VE by preserving the existing motion data of the model. Our approach is efficient enough to be used in real-time applications such as virtual try on (VTO) where it is possible to customize the avatar by a specific body measurement. Furthermore, the same method is used to increase the visual realism of virtual crowds from a fixed amount of templates by generating a range of differently sized avatars. To achieve this, we use the joint hierarchy information of the attached skeleton to automatically segment the body into regions. The segmentation process is based on the joint positions and so the length deformations are performed along the bones. This approach makes it possible to deform the model independently from its posture and precisely adapt the skeleton according to the new body shape. We use the ANSUR anthropometric body measurement survey [7] to create different size template model instances.

2 Related work

Earlier research on the model deformation methods started with Barr's [3] work on parametric shapes called superquadrics. Scheepers used similar parametric shapes to anatomically model the human body muscles [14]. Chadwick [5] achieved dynamic muscle effect on top of the skeleton with a free-form deformation (FFD) technique to animate the human body model. Our approach is based on the method named Scodef [4] which is a variant of FFD and explained in Sect. 3.3.1.

Anthropometry based human body modeling is first introduced by Grosso et al. [8]. A human body model is segmented into groups according to joints and joint deformation is applied for animation. In Grosso's development, a body model is manually segmented into 24 polyhedral geometric primitives with length, width, and depth parameters. In contrast to our method, model representation is not smooth and the continuity of the segments are not possible because of the distinct polyhedral geometric primitives constructing the body. Instead of using polygonal methods, Jianhua [9] divided the model into slices and a radius of each slice is scaled to achieve the muscular deformation effect.

An earlier version of the example based human body deformation method is presented by Seo et al. [15]. The method searches a database of scanned body models according to the user specified body parameters. An animating template model is then fitted into the resulting static scan body to take its shape. Similarly Allen et al. [1] developed an example based approach to transfer a template body model onto a scanned data. They used 250 scanned body model data to demonstrate parameterization and reconstruction. Anguelov et al. [2] presented a pose space deformation of the body model by using a body scanner. When scanning the same person in different poses, a deformation space is generated. The proposed framework generates the desired body shape according to the parameters such as angles of the joints and the eigen-coefficients of the shape.

The majority of the studies on human body modeling are focused on a specific part or layer of the body such as the skeleton, skin, fat tissue, etc. or are very general without any standardization. Among deformation methodologies, mainly the example based approaches worked on parametric model generation from a template model. Even though requesting a specific model from a database that corresponds to the desired parameters, this approach takes long response time and is a bit cumbersome for real-time applications. In [10], even though the proposed method is appropriate for real-time applications, it is used to segment the static model manually without considering the underlying skeleton. An improved version of this work in [11] automatically segmented the body into regions but since the skeleton is approximately scaled to fit into the mesh, deformation was evident around the joint regions and the model must be in a specific posture.

3 Size variations

In CG, almost all the application fields use the virtual characters as part of the simulation environment. Creating various virtual characters to populate the environment requires intensive human effort to intuitively generate them. There exist several approaches to achieve the variations between the individual characters. Some of these are listed as: the surface rendering techniques with different physical parameters, image mapping with different textures, mesh deformation, etc. Among these, the mesh deformation to generate size variations is the most attractive one. Like all species, human beings have a known shape mainly with size variations that are difficult to model as virtual characters. The main problem with these virtual characters is the way of their structural representation in the software level of the graphics system. Most virtual entities can be represented parametrically but in the case of the human body, yet there is no definite way to parametrically define the exact body properties. Using the anthropometry standards as size variation parameters, we define a new method to parametrically represent the human the body shape and its underlying layers. In contrast to existing methods, first we use industry standard parameters to define a model. These parameters correspond to precisely defined mesh segments based on the character skinning data. Second, we adapt the underlying skeleton to match the joint positions with the correct mesh segment after any size modification on the model. Moreover this method is independent from the model posture and can be applied on any skinned character to generate variances.
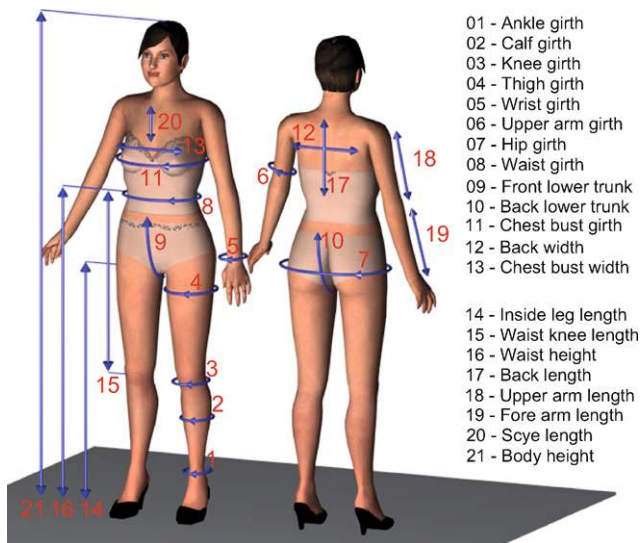
Fig. 1 Anthropometric human body measurement landmarks

01 - Ankle girth
02 - Calf girth
03 - Knee girth
04 - Thigh girth
05 - Wrist girth
06 - Upper arm girth
07 - Hip girth
08 - Waist girth
09 - Front lower trunk
10 - Back lower trunk
11 - Chest bust girth
12 - Back width
13 - Chest bust width

14 - Inside leg length
15 - Waist knee length
16 - Waist height
17 - Back length
18 - Upper arm length
19 - Fore arm length
20 - Scye length
21 - Body height

Fig. 2 Kinematic structure that is used to animate the models

3.1 Anthropometry

Anthropometry is the science of body measurement to analyze the human physical variations. Since the virtual human models have become important in the computer graphics field, the anthropometric data start to be used for parametric body definition. For example, the textile applications such as VTO, need anthropometric features to generate a virtual character and simulate clothes on the character. Also, generating virtual crowds with a variety of realistic characters requires this information for parametric modeling. Figure 1 represents several anthropometric measurements that are used by tailors, designers, ergonomists, etc. Some of these landmarks may differ from one application area to another with different names or order. It is possible to reproduce some of these measurements from the combination of other ones. So, these sets of measurements may be decreased to a smaller set or increased to have more variety.

Based on the human anthropometry, there exist several internationally common measurement guidelines such as ISO7250 (Basic human body measurements for technological design) and EN13402 (European standard for labeling clothes sizes). Using the ISO7250 standards, several main body measurements (see Fig. 1) are extracted and used as parameters to define a template body model. Referring to these parameters, the body model is segmented into regions that can be deformed to generate size variations.

3.2 Model segmentation

Like the clothing industry, we use the industry standard landmarks (see Fig. 1) to deform the virtual characters at specific regions to individualize them. Each of these landmarks is used to define the shape characteristics of a model.
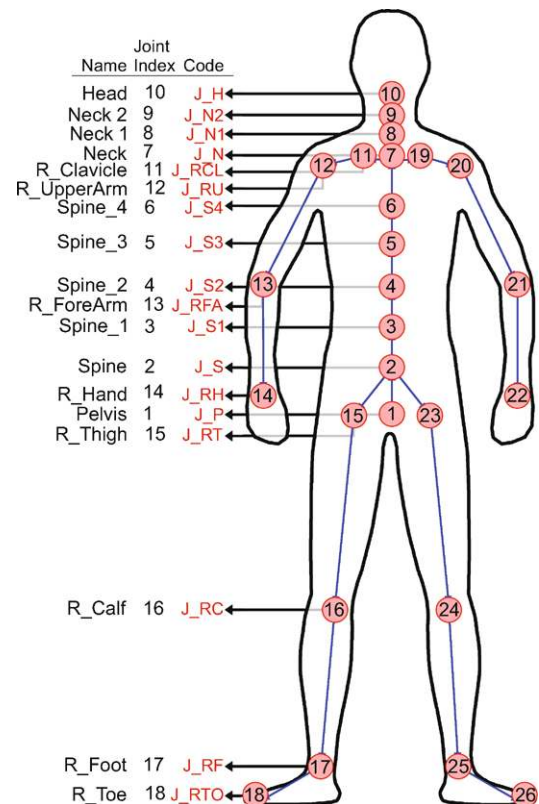
In our approach, we divide the body into smaller segments each of which corresponds to specific measurement landmarks. To achieve size variation under a landmark, we deform the corresponding segment of the mesh. One major problem is to define the boundaries of these segments precisely so that the predefined landmarks will correspond to the same regions in all models. Another problem is to find the appropriate deformation space and the dimension that will generate a model and posture independent size variations. As a solution, we use the skinning data of the model to overcome these problems.

3.2.1 Linear blend skinning

As we are using the skinning data for model deformation and segmentation, in this section we summarize the LBS method by emphasizing the bindpose features that we adapt into our method. The LBS is a widespread method used to animate a virtual character. This skinning method is based on a skeleton, skin (mesh), and per-vertex weights. The skeleton is a rooted tree located in the mesh (see Fig. 2). Each node of the skeleton tree corresponds to a joint, and an edge between two neighboring joints is a bone. There is an attachment relation between a vertex and all the bones. When any of the bones move, the attached vertex follows the bone with the amount of predefined weight between the vertex and the bone.
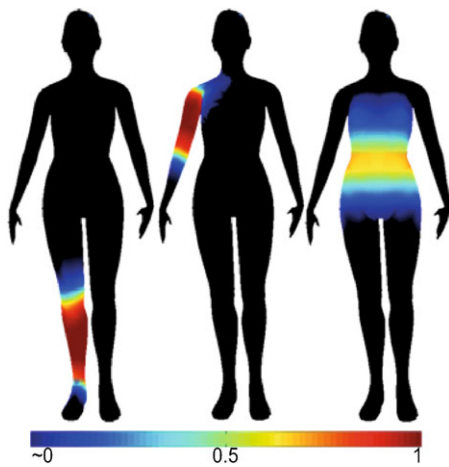
Fig. 3 Color coded skin weights of vertices affected per joint. From left to right: calf, upper arm and spin joints

In theory, per bone, all vertices are attached to a bone which is transformed into the local coordinate space (LCS) of that bone and then transformed back into the new animated position. For each root joint of a bone in the skeleton system, there is a corresponding animation matrix per keyframe $A_{i,t}$ of the animation. Generally, these matrices are generated by using motion capture devices. To find the final position of a vertex at a specific keyframe, the following equation is used:

$$v'_{j,t} = \sum_{i=0}^{n} \left((v_j \times BSM) \times BP_i \times A_{i,t} \right) \times W_{i,j}. \qquad (1)$$

Here, v_j is the jth vertex of the model to be animated. $v'_{j,t}$ is the new position of the vertex v_j that is animated into keyframe t. BSM is the bindshape matrix which transforms the mesh onto the skeleton. BP_i is the ith joints bindpose matrix that transforms the vertex into the LCS of that joint. $A_{i,t}$ is the pose matrix that transforms the vertex into the animated position at tth keyframe. And finally the $W_{i,j}$ is the weight of the jth vertex that defines how much the vertex is affected by the ith joint (see Fig. 3). Weight value ranges between 0 to 1. If v_j is close to the ith joint, then the weight is close to the value 1, if it is away from the joint its value gets closer to 0. For each vertex, contributions of all joints are blended with a summation and this equation is applied on each vertex v_j of the model to find their new animated position on the frame t.

In the following three columns of Fig. 3, the color-coded skin weights of vertices that are affected by three different joints are illustrated. Vertices illustrated with a black color means that they are not affected by the corresponding joint's movements.

There is a separate list of affected vertex indices and the corresponding weights assigned per-joint. These lists always include vertex indices from the neighboring joints but most of the time they also include vertices from neighboring mesh regions, i.e., the list of vertex indices affected by arm joint may include vertex indices of the torso region with weight values closer to zero. These defected skinning values are assigned during the design stage of the models because it is a hand manipulated operation and we call them *defected vertices*. As the weights of these vertices are near to zero, they are not affected during the arm movements. In Sect. 3.2.3, we will mention the usage of per-joint affected vertex indices and how to eliminate defected skinning data. Also, in the following section, we will mention the use of per-joint BindPose matrices.

3.2.2 Local coordinate space

Our method is based on the LBS data where the vertices of the mesh are segmented into groups within the joints' LCS. Transforming the mesh vertices V into the LCS of joint J_i, where i corresponds to the ith joint, is defined by the function L as:

$$L(V, J_i) = MR_{J_i} \times MT_{J_i} \times V, \qquad (2)$$

where $L(V, J_i)$ is the new position of the vertices V in the LCS of a joint J_i. MT_{J_i} is the transform matrix that transforms the joint J_i into the origin. MR_{J_i} is the rotation matrix that rotates the joint J_i to make the model look to the front and to position the child joint of the J_i on the X axis. In the LBS method, the multiplication of these transformation operators is called the BindPose matrix BP_i of joint J_i and in our approach it is adapted to define a common deformation domain among different models and body segments.

In Fig. 4, vertices that are affected by the calf joint (see Fig. 3) and their bounding box that is transformed into the LCS of the calf joint are illustrated. As a result of this transformation's characteristics, the bone lies on the X axis where the root joint calf is located on the origin.

3.2.3 Mesh segmentation

Segmentation is the major step to define the deformation parameters on a model. Using the coordinates of the skeletal joint positions (see Fig. 2), we divide the body into segments which are then used to deform the model for size variations. The main advantage of using joint positions for segmentation is to define precise boundaries that overlap with the joints. It is evident that the body length variations occur along the bone length which means a direct relation between the skin and the underlying skeleton. To achieve a one-to-one mapping between the mesh deformation and the bone lengths, we define the boundaries of the mesh segments exactly at the point of joints. Applying a length deformation on the mesh along with the skeleton adaptation preserves

Fig. 4 (**a**) Calf segment of the model in figure mode. (**b**) Vertices transformed into the LCS of calf joint
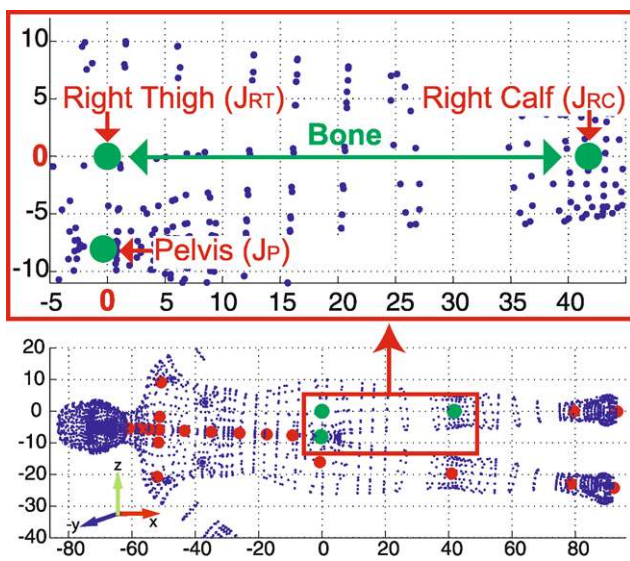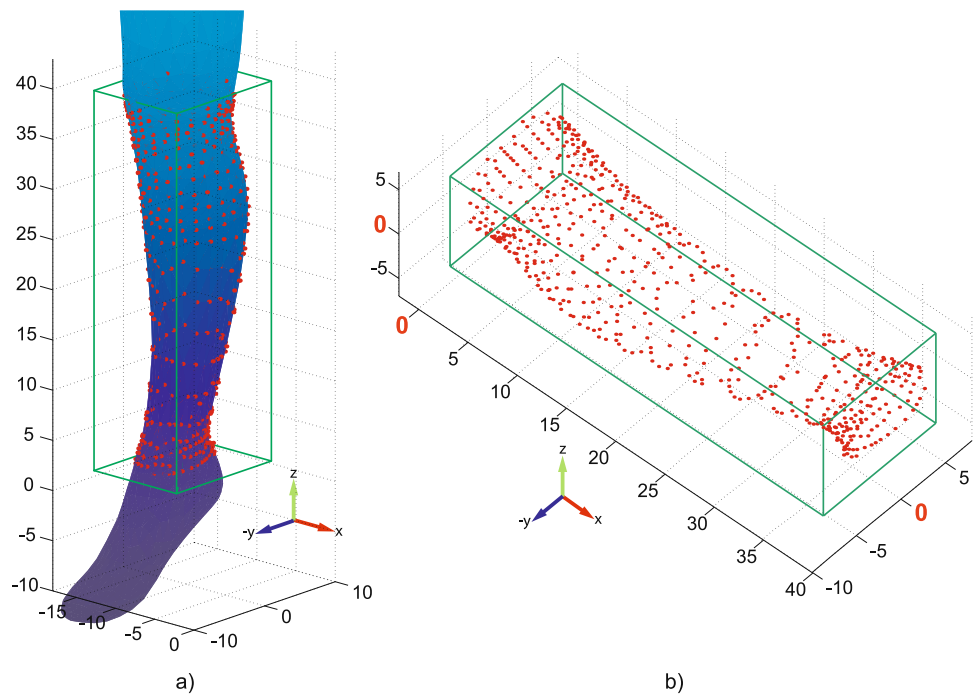

Fig. 5 Vertices in the LCS of J_{LT}. Child joint $J_{LC} . z = 0$

this relationship and prevents any potential artifacts in the character animation stages.

As an example of defining the body segments that are based on joint locations, the following operation details the stages to define the right thigh segment. As illustrated in Fig. 5, first the model vertices are transformed into the LCS of the RightThigh joint J_{RT}. After this BindPose transformation, the right thigh joint is placed on the origin, and then rotated to place the child joint J_{RC} on the X axis. Finally, the vertices are filtered according to the Pelvis (J_P) and RightCalf(J_{RC}) joint coordinates within the LCS of J_{RT}. In

the case of the right thigh, the vertex filtering process is handled by the following operation:

$$S_{RT} = V . x > 0 \quad \& \quad V . x < J_{RC} . x$$
$$\& \quad V . z > J_P . z, \tag{3}$$

where V is the vertices affected by the RightThigh joint and S_{RT} is the vertices of the right thigh segment. Using (3) within the LCS of J_{RT}, vertices with x coordinates between 0 and $J_{RC} . x$, and z coordinates greater than $J_P . z$ are filtered. The result of this query includes the thigh vertices with two exceptions. First, if the arms of the model are in the inverted V posture, so closer to the torso, then the query with filter $J_P . z$ will not exclude the arm vertices from the result. This procedure may also apply to other body segments depending on the model posture. Second, if there is a skinning defect then the list of affected vertices V may include undesired vertices, i.e., from the left thigh.

To eliminate these exceptional cases, initially we detect the vertices of the head segment and following these operations we start detecting the main body limb segments: (left/right) arms, (left/right) legs and the torso region. Later on, we apply segmentation filters on these main vertex regions instead of the whole body vertices. Referring to (3), we detect the head segment similarly with the following equation:

$$S_H = V . x > 0, \tag{4}$$

where V is the list of vertices that are affected from the head joint and in its LCS. After the head segment, we continue

Fig. 6 (**a**) Arm's opening degree α is calculated in the LCS of $J_{(L/R)CL}$. (**b**) Arm is transformed into T posture. (**c**) New T posture body in LCS of $J_{(L/R)U}$ is rotated 45° around Y axis
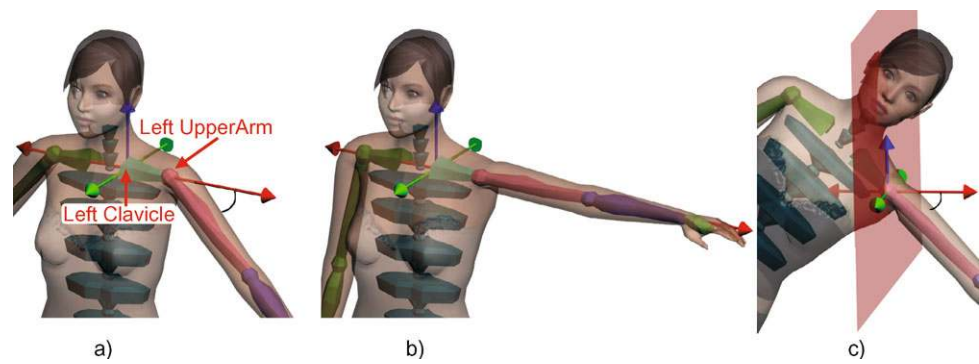
detecting the following limbs in sequence: arms, legs, and finally the torso. Among them, the arms are most of the time in indeterministic posture. So, we apply a specific method to detect them and this method can also be applied to legs in case of dealing with models that are in sitting posture, etc. In the following section, we describe this method to detect the arm regions of the model independently from the body posture.

3.2.4 Posture independent segmentation

Depending on the posture of the model (i.e., the inverted V-posture where the arms are bent closer to torso), the right thigh segment may contain vertices from the arm segment as mentioned or vice versa. So, we transform the arms into T posture (where the arms are parallel to the floor) by finding the opening degree α of the upper arm bone with the floor (see Fig. 6(a)). To do this, firstly we transform the whole model vertices into the clavicle joints LCS. Because the UpperArm joint is the first child of the clavicle joint, after transformation it lies on the X axis.

Secondly, by using the skinning information we rotate the upper arm joint with the degree of $-\alpha$ around the Y axis, so the arms become parallel to the floor (see Fig. 6(b)). And lastly, the new T posture body vertices are rotated 45° around the Y axis in the LCS of the upper arm joint. After all these operations, excluding the head segment vertices, the vertices over the positive side of the X axis are selected as left (S_{LA}) or right (S_{RA}) arm vertices segments.

For the leg regions, we use the filter $S_{legs} = V \cdot x > 0$ in the LCS of pelvis joint where V is the whole model vertices. After detecting the vertices of legs, just these vertices are again transformed into the LCS of the pelvis joint and in this space vertices on the positive z axis defined as right leg and the rest are left leg. Excluding head, arm, and leg segments from the whole body, we find the torso segment.

3.2.5 Defining smaller segments

Achieving size variances around the landmarks that are illustrated in Fig. 1 requires the deformation of smaller regions. Using the joint locations and the mentioned skinning information, we define detailed subregions out of the main limbs that we previously detected. In this subsequent segmentation process, we do not consider the *defected vertices* among different regions or the *shared vertices* in-between two neighboring limbs that share the same joint. *Shared vertices* come out because of the numerical precision errors that occur in the LCS transformations, i.e., a vertice on the knee that resides over calf joints may belong to both thigh or calf segments. The torso is the common region that is neighbouring with the other main limbs. Using the set operations, we define the torso region by excluding the other regions from the whole body vertices. This approach makes it possible to eliminate the shared vertices between the common region torso and the others. For defining the smaller segments out of the main regions, we again refer to the same approach that we used for detecting the main limbs. But this time, we intersect the result of the filtering operation with the main body limb that overlaps with the smaller segment. So, as in our thigh segment example discussed in the previous paragraphs, i.e., if the right thigh segment includes defected vertices from the left thigh segment or any arms, etc. then finding the intersecting vertices between the right leg and the initial right thigh segment will guarantee the error free detection of the desired vertices.

The above mentioned problems are also valid for the neighboring smaller segments. So, we start detecting the smaller segment within a main limb from the leaf joint of the underlying skeleton of that main region, i.e., for the right leg region, we first detect the right foot segment in the LCS of RightFoot joint. After testing the intersection with the right leg, we exclude the resulting right foot segment from the right leg main region. Subsequently, we do the same for the right calf segment and then finalize the segment definition on the right leg with the right thigh segment. In Fig. 7, we illustrate the smaller segments that we detected with the mentioned method.

Eliminating the defected and shared vertice artifacts is important both in the deformation and the animation of the model. So, the precise segmentation is very important to achieve robust and smooth size variations. Even with a single vertex shared between two segments produces undesired
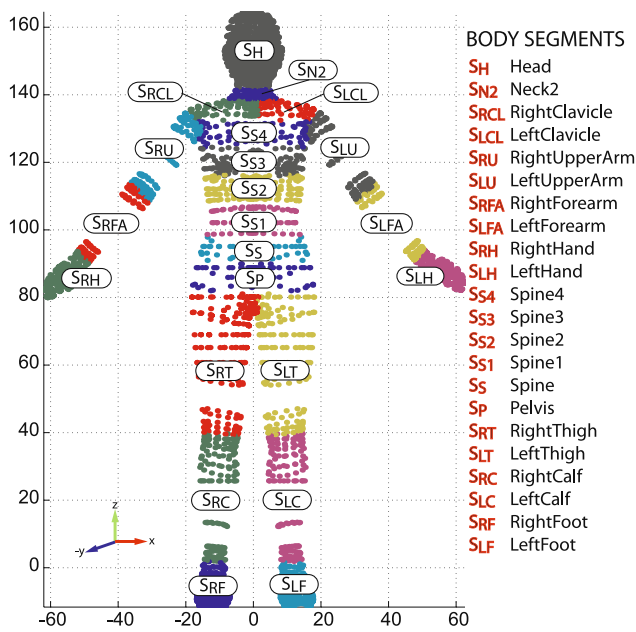
Fig. 7 Smaller body segments defined over major limbs

Fig. 8 SCODEF deformation on the belly region and the plot of corresponding user defined deformation functions

artifacts in the model deformation stage. In this section, we explain the method to overcome these problems.

3.3 Rapid deformation

Deformation methods can be categorized under two broad headings: physically based and geometry based deformations. There is a precise balance between the efficiency and the accuracy factors of the output of these two main methods. In the case of real-time applications, geometry based deformation techniques are widely used because of their efficiency. In general, physically based methods consider all the layers of the model with its physical material structure. But in geometry based methods, generally the model surface is deformed as in the LBS methods. As our target application field is real-time digital mannequins that are mainly used for cloth simulation, we develop our method on top of geometric deformation approaches.

3.3.1 Variation of a free-form deformation

SCODEF [4] is a type of geometry based free form deformation method that is efficient enough to be used in real-time applications. The underlying deformation is constrained within a predefined region and the vertices under this region are displaced in the direction of their normal vectors. To apply this deformation, the constrained region is scaled to fit in an axis-aligned unit cube. The amount of the displacement is defined by a set of spline functions where the user can adjust the curvature. Depending on the scaled 3D coordinate of the vertex in the unit cube, the deformation function returns the corresponding displacement multiplier.
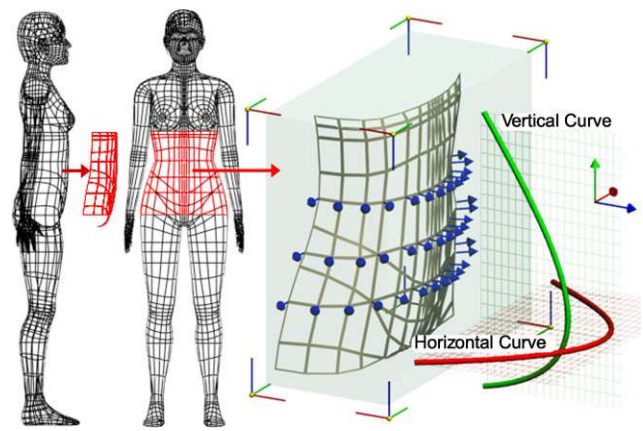
In Fig. 8, the belly region (front half of $S_{S1} + S_S + S_P$) of the body is scaled into a unit cube and two spline functions in horizontal and vertical directions, are used as a displacement multipliers.

The method that we use to deform the body regions is the same as the one explained in the paper by Kasap and Thalmann [10]. One of our contributions is to automatically define the body regions by using the underlying skeleton space independently from its posture. So, the region boundaries are precisely defined with respect to the joint positions. Another contribution is to redefine the length deformations in the LCS of the corresponding skeleton and size the bone together with the corresponding vertices. One of the advantages is that all these operations are independent from the model posture. This new deformation technique is explained in the following sections.

3.4 Length deformation & skeleton adaptation

Two types of deformations may be applied on the model: Girth and Length deformations. The consequence of the length deformation without an adaptation is a corruption on the existing motion of the model. This is because the skeleton does not fit inside the skin and the LBS method deforms the model in the original LCS of the joints (see Fig. 9). To prevent this problem, we both deform the mesh and adapt the skeleton in the new LCS of the affected joint.

Unlike the girth deformations, only the length deformations are applied in the LCS of the corresponding joint. Because of the posture of the arms and legs which are not exactly parallel or perpendicular to the floor, scaling the vertices in the world coordinate produces improper deformations. As we know that the main arm and leg bones are in a straight structure, we change the limb length in the LCS of the corresponding bone. This is because the parent and child joints of the bone lie on the X axis (see Fig. 5) which means a straight structure.
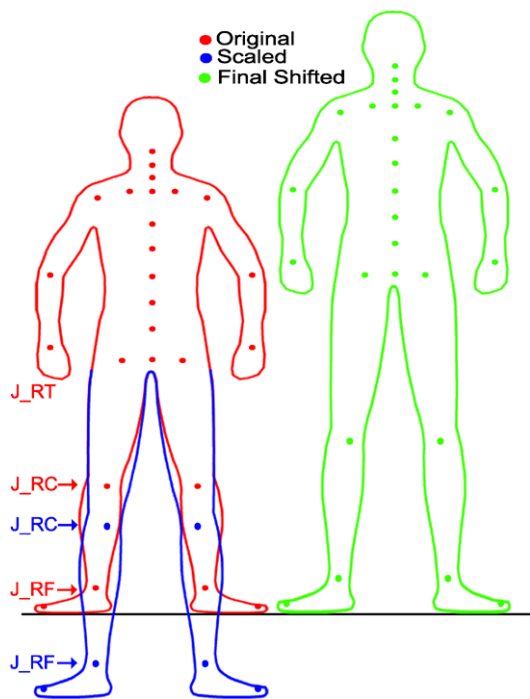
Fig. 9 SCODEF deformation on the belly region and the plot of corresponding user defined deformation functions

For example, to change the right thigh length, firstly we transform the vertices S_{RT} and the first child joint J_{RC}, into the LCS of J_{LT}. Secondly, we scale both the right thigh vertices and the position of the first child joint J_{RC} in this space. This scale operation is performed just in the direction of the X axis. This is because, in the L_{CS}, the parent joint J_{RT} transformed into the origin, and the first child joint J_{RC} lies on the X axis. This configuration gives the opportunity to scale the leg in the direction of the bone and independently from its posture. After scaling, the amount of shift in the position of J_{RC} is calculated. Then all the child joints and child vertex segments (i.e. calf, foot) are shifted with the same amount in their LCSs. After all these operations, they are transformed back into the original space. In the case of body height changes, the pelvis joint (skeleton root) is also shifted to place the feet on the floor (see Fig. 9).

3.5 Body measurements as parameters

The method that is explained scales or deforms the anthropometric regions of the model to achieve different size variances. On the other hand, most of the applications such as VTO specify the body measurements in centimeters and not in scale multipliers. Also to create virtual crowds, it is more realistic to use correct body measurement proportions based on anthropometric measurement surveys and not again random scale multipliers. Based on the body segments (see Sect. 3.2.3) and skeleton joint coordinates, the anthropometric measurement landmarks that are presented in Fig. 1

Table 1 Body measurement formulations

ID	Type	Description
1	G	$C(SL_{YZ}(S_{RF}, J_{RF}, 0))$
2	G	$C(SL_{YZ}(S_{RC}, J_{RC}, D(J_{RC} . x, J_{RF} . x)/3))$
3	G	$C(SL_{YZ}(S_{RC}, J_{RC}, 0))$
4	G	$C(SL_{YZ}(S_{RT}, J_{RT}, D(J_{RT} . x, J_{RC} . x)/4))$
5	G	$C(SL_{YZ}(S_{RH}, J_{RH}, 0))$
6	G	$C(SL_{YZ}(S_{RU}, J_{RU}, D(J_{RU} . x, J_{RFA} . x)/4))$
7	G	$C(SL_{YZ}(S_P, J_P, D(J_P . x, J_S . x)/2))$
8	G	$C(SL_{YZ}(S_{S1}, J_{S1}, D(J_{S1} . x, J_{S2} . x)/2))$
9	OG	$L(SL_{XY}([S_{RT}, S_{LT}, S_P, S_S, S_{S1}], J_P, 0) . y > 0)$
10	OG	$L(SL_{XY}([S_{RT}, S_{LT}, S_P, S_S, S_{S1}], J_P, 0) . y > 0)$
11	G	$C(SL_{YZ}(S_{S3}, J_{S3}, J_{S3} . x))$
12	L	$T = SL_{YZ}(S_{S4}, J_{S4}, D(J_{S4} . x, J_N . x)/2) . y < 0$ $D(Min(T . x), Max(T . x))$
13	L	$T = SL_{YZ}(S_{S4}, J_{S4}, D(J_{S4} . x, J_N . x)/2) . y > 0$ $D(Min(T . x), Max(T . x))$
14	L	$D(J_P . z, J_{RTO} . z)$
15	L	$D(J_{S1} . z, J_{RC} . z)$
16	L	$D(J_{S1} . z, J_{RTO} . z)$
17	L	$D(J_{N2} . z, J_{S2} . z)$
18	L	$D(J_{RU} . z, J_{RFA} . z)$
19	L	$D(J_{RFA} . z, J_{RH} . z)$
20	L	$D(J_N . z, J_{S4} . z)$
21	L	$D(Min(V . z), Max(V . z))$

are automatically extracted from the underlying model. Appropriate sections of the corresponding segments are intersected with a plane and the intersection coordinates are used as landmarks to determine the *girth length* measurements. For the *length* measurements, either the joint coordinates or the min/max vertex coordinates are used. To create a specific size body, scale parameters are adjusted to achieve the desired measurement.

3.5.1 Extracting measurement landmarks

There exist three types of measurements that are extracted from the model; *Length*(L), *Girth*(G), *OpenGirth*(OG). Formulation to extract these measurement landmarks are presented in Table 1. According to these formulations, a set of several vertex indices are determined. Any time desired, these indices and so the actual coordinates of the corresponding vertices are used to make the measurement. To make length measurements, either the indices of two vertices or the coordinates of the two joints are used and the actual distance between these two parameters is calculated. To make girth or open girth measurement, a set of vertex indices are used. Assuming these vertices are laying on a slice of curve that is extracted from the body, the length of the curve is calculated. Table 1 consists of formulations that
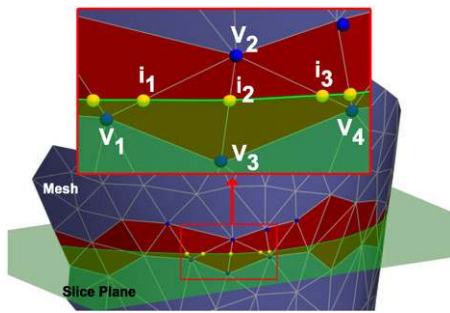
Fig. 10 Slice of vertices extracted for girth measurement

are used to extract these measurement indices. Definitions of the functions in the following table are:

V: Model vertices.

$D(X, Y)$: Difference between the two parameters.

$L(X)$: X is a set of vertex indices. Assuming these vertices lie on a curve, then the length of this curve is calculated.

$C(X)$: X is a set of vertex indices. Assuming these vertices lie on a polygon, then the circumference of this polygon is calculated.

$SL_A(B, C, D)$: Intersects a plane A with a mesh B and returns a slice of vertices from the intersection points. Firstly,

mesh B is transformed into LCS of C. Secondly, plane A is positioned at the location D. A defines the two varying dimensions of the plane and so D is defined in the third fixed dimension.

Slicing the mesh generates extra triangles and requires the computation of new texture coordinates. As a consequence, a higher number of triangles negatively affects the performance. So, instead of physically slicing the mesh and referring to Fig. 10, first the edges of the triangles that intersect with the plane are found. Second, the indices of the two vertices of the edge (i.e., v_2 and v_3) and the intersection point (i_2) as a ratio (see (5)) between these two vertices is calculated.

$$r = \frac{v_2 - i_2}{i_2 - v_3}. \tag{5}$$

So, each intersection point is represented with two vertex indices and ratio parameters. In the case of a measurement, the actual deformed vertex coordinates are interpolated with the ratio to find the actual coordinate of the intersection point and this operation is performed on a set of intersection parameters that are defined for the measurement.

If the extracted vertices from the intersection slice are represented as $S_A(B, C, D) = \{(v_1, v_2, r_1), (v_2, v_3, r_2),$

Fig. 11 Different size models generated from a single template animated model

Table 2 Body measurement statistics (in centimeters) over the landmarks that are illustrated in Fig. 1. ANSUR measurement IDs that correspond to our landmarks and standard deviations (SD)

Our landmarks		ANSUR	Min	Max	Avrg	SD
	ANSUR landmark correspondences with statistics					
01	Ankle G.	06	159	249	205	12
02	Calf G.	29	285	459	352	23
03	Knee G.	72	302	461	365	23
04	Thigh G.	104	454	748	580	45
05	Wrist G.	127	673	939	790	38
06	Upper Arm G.	12	213	371	281	22
07	Hip G.	24	787	1189	966	60
08	Waist G.	114	610	1108	791	82
09	Front Low. T.	40–43	214	426	300	24
10	Back Low. T.	43	207	413	306	25
11	Chest Bust G.	34	711	1176	907	63
12	Back W.	11	301	417	362	17
13	Chest Bust W.	33	222	375	279	19
14	Inside Leg L.	39	594	948	771	44
15	Waist Knee L.	119–73	426	637	523	27
16	Waist H.	119	802	1175	982	48
17	Back L.	111	363	555	442	24
18	Upper Arm L.	92	282	401	335	17
19	Fore Arm L.	88	157	312	243	15
20	Scye L.	90	142	235	185	14
21	Body H.	100	1428	1870	1629	63

H.: Height, L.: Length, G.: Girth, W.: Width

$(v_3, v_4, r_3), \ldots, (v_n, v_1, r_n)\}$ then the open girth measurement M_{OG} and the girth measurement M_G of a specific landmark are defined as:

$$M_{OG} = \sum_{i=1}^{n} (v_i + v_{i+1}) \times r_i,$$

$$M_G = \sum_{i=-1}^{n-2} (v_{(i \bmod n)+1} + v_{((i+1) \bmod n)+1}) \times r_{(i \bmod n)+1}.$$

(6)

Indices of the vertices that are used for the measurement computation are extracted only one time at the initialization stage of the template model. As only the vertex positions are changing during the deformation stage, index values referring to these vertices stay constant.

3.5.2 Size variation from anthropometry database

To size the body model into a specific measurement, proxy computation is performed. Instead of deforming the whole mesh, only the slice vertices are deformed by a varying deformation multiplier. Once the correct deformation multiplier is found, it is applied on the whole mesh to achieve the desired model size. The multiplier value varies between the min/max range [0.1, 10], which is quite large scale that covers all body size ranges, i.e., from a template model with 1 meter body height, it is possible to generate 10 cm to 10 m height models. As we use the anthropometry database to size the models, a *reasonable* scale multiplier (i.e., not 10 m height) is found in between this min/max range. To find a correct multiplier value that corresponds to a specific measurement, an iterative approach as in the binary search algorithm is used. The scale multiplier is changed within a range to deform just the small set of proxy vertices that are specified for measurement. The computation cost of this iterative process is $O(\log n)$.

For the real body measurements, the ANSUR anthropometric body measurement database [7] of 2200 female subjects is used. The final report on this survey illustrates the 132 measurement landmarks which are a superset of our 25 measurement landmarks illustrated in Fig. 1. To generate size variations in our simulations, we randomly pick a female subject from this database and scale our template model according to the fetched measurements record.

In addition, we analyzed the ANSUR database and generated the statistical results represented in Table 2. According to the average measurement values and the standard deviations, we generate random size parameters and generate the corresponding models.

4 Conclusion

This paper presented a method to create size varying population with real-time efficiency. The major difference of the method from others is that both the segmentation and the deformation take place at the joint level of the skeleton that is attached to the template model and these are independent from the model's posture. This approach makes it possible to have precise deformations together with the underlying skeleton and so the side-effects of wrong joint placement after deformation is eliminated. Furthermore, the anthropometric body measurement database is used to generate body size variations. Some sample models generated with the mentioned method are exemplified in Fig. 11. Although our aim is to efficiently create variation in different size models by precisely adapting the model's skeleton, it does not consider the motion adaptation problem. As the model's size changes, the underlying motion data should also be adapted to the new size. This is because a model with longer legs will take more proportion of step length than the model with shorter legs. Unless the motion is adapted to the new body size, there will be a foot skating problem in the animation. We believe that the on-line motion retargeting method [6] will solve it with real-time efficiency. Also, the realism of the population can be increased with the method mentioned in [13], which applies different textures and accessories on the model without extra computation cost at runtime.

References

1. Allen, B., Curless, B., Popovic, Z.: The space of human body shapes: reconstruction and parameterization from range scans. ACM Trans. Graph. **22**(3), 587–594 (2003)
2. Anguelov, D., Srinivasan, P., Koller, D., Thrun, S., Rodgers, J., Davis, J.: Scape: shape completion and animation of people. ACM Trans. Graph. **24**(3), 408–416 (2005)
3. Barr, A.: Superquadrics and angle-preserving transformations. IEEE Comput. Graph. Appl. **1**(1), 11–23 (1981)
4. Borrel, P., Rappoport, A.: Simple constrained deformations for geometric modeling and interactive design. ACM Trans. Graph. **13**(2), 137–155 (1994)
5. Chadwick, J.E., Haumann, D.R., Parent, R.E.: Layered construction for deformable animated characters. In: SIGGRAPH'89: Proceedings of the 16th Annual Conference on Computer Graphics and Interactive Techniques, pp. 243–252. ACM Press, New York (1989)
6. Choi, K.J., Ko, H.S.: On-line motion retargetting. In: Proceedings of the 7th Pacific Conference on Computer Graphics and Applications, PG'99, p. 32. IEEE Computer Society, Washington (1999)
7. Gordon, C.C., Churchill, T., Clauser, C.E., Bradtmiller, B., McConville, J.T., Tebbetts, I., Walker, R.A.: 1988 Anthropometric survey of U.S. Army personnel: summary statistics interim report. Tech. Rep. NATICK/TR-89/027, U.S. Army Natick RD&E Center, Massachusetts (1989)
8. Grosso, M., Quach, R., Otani, E., Zhao, J., Wei, S., Ho, P., Lu, J., Badler, N.: Anthropometry for computer graphics human figures (1987)
9. Jianhua, S., Thalmann, N.M., Thalmann, D.: Human skin deformation from cross-sections. In: Computer Graphics Int, pp. 9–14. (1994)
10. Kasap, M., Magnenat-Thalmann, N.: Parameterized human body model for real-time applications. In: Proceedings of the 2007 International Conference on Cyberworlds, pp. 160–167. IEEE Computer Society, Washington (2007)
11. Kasap, M., Magnenat-Thalmann, N.: Sizing avatars from skin weights. In: Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology, VRST'09, pp. 123–126. ACM Press, New York (2009)
12. Magnenat-Thalmann, N., Laperrière, R., Thalmann, D.: Joint-dependent local deformations for hand animation and object grasping. In: Proceedings on Graphics Interface'88, pp. 26–33. Canadian Information Processing Society, Toronto (1988)
13. Maim, J., Yersin, B., Thalmann, D.: Unique character instances for crowds. IEEE Comput. Graph. Appl. **29**, 82–90 (2009)
14. Scheepers, F., Parent, R.E., Carlson, W.E., May, S.F.: Anatomy-based modeling of the human musculature. In: SIGGRAPH'97: Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques, pp. 163–172. ACM Press/Addison-Wesley, New York (1997)
15. Seo, H., Magnenat-Thalmann, N.: An example-based approach to human body manipulation. Graph. Models **66**(1), 1–23 (2004)

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