Feature-Based Human Model for Digital Apparel Design

Shuxia Wang, Member, IEEE, Shengfeng Qin, Member, IEEE, and Congying Guan

***Abstract*—3D body scanning technology opens opportunities for virtual try-on and automatic made-to-measure apparel design. This paper proposes a new feature-based parametric method for modeling human body shape from scanned point clouds of a 3D body scanner [TC]². The human body model consists of two layers: the skeleton and the cross-sections of each body part. Firstly, a simple skeleton model from the body scanner [TC]² system has been improved by adding and adjusting the position of joints in order to better address some fit issues related to body shape changes such as spinal bending. Secondly, an automatic approach to extracting semantic features for cross-sections has been developed based on the body hierarchy. For each cross-section, it is described by a set of key points which can be fit with a closed cardinal spline. According to the point distribution in point clouds, an extraction method of key points on cross-sections has been studied and developed. Thirdly, this paper presents an interpolation approach to fitting the key points on a cross section to a cardinal spline, in which different tension parameters are tested and optimized to represent simple deformations of body shape. Finally, a connection approach of body parts is proposed by sharing a boundary curve. The proposed method has been tested with the developed virtual human model (VHM) system which is robust and easier to use. The model can also be imported in a CAD environment for other applications.**

***Note to Practitioners*—Automatic made-to-measure for mass customization has become one of the important developments for the apparel industry. 3D body scanning technologies are used to capture a virtual clone of an individual human body model for mass customization. However, these methods have failed to overcome two critical problems. First, the extremely expensive cost of the equipment prevents it from wide applications in garment industry. Second, the data format either in the original point clouds or simplified mesh models is not easily to be linked to a parametric model, which can be automatically modified to different shapes by the user parameter inputs. For this reason, this paper intended to build a parametric human body model, which can represent an individual body by inputting some key dimensions which is more than the traditional manual measures but drastically fewer than the 3D body scanner data.**

***Index Terms*—Human body modeling, apparel design, parametric modeling, apparel-fit-to-body issues**

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I. INTRODUCTION

TODAY, there is an increasing demand for the involvement of computer aided design in apparel and entertainment industries. The automatic made-to-measure for mass customization has become one of the important developments for the apparel industry. Anthropometry, body model analysis, garment style selection, clothing design, clothing ordered and production can be organically integrated by using 3D scanning technology, computing and internet technology in order to realize fast and efficient digital apparel production chain [1]. From above developments, it can be easily observed that digital human body research is an essential part for any further apparel design application, which provides garment designers with a virtual clone to design, to try on and to show their production in a whole virtual environment. It concerns the 3D representation of individual human body, that is, to build up a virtual human body to match an individual body. This is critical for apparel industry which isn't as same as the entertainment industry that is contented with realistic appearance and efficiency. The purposes of constructing human body are threefold: firstly, designer would like to design clothing for supporting custom-made garment on individual human body; secondly, designer/customers would like to evaluate design clothing without the need for actually producing it; finally, for online shopping, apparel industry would like to develop virtual try-on applications allowing consumers to see how designed clothing fit on their individual body. Furthermore, the virtual human body not only can be used in apparel industry, but also can be used in the other domains [2, 3].

In recent decade, 3D body scanning technologies are used to capture a virtual clone of an individual human body model. 3D scanning technique can capture body shapes accurately and the final output is a single static mesh with a few million vertices. Generally, the raw data resulting from a scanning process cannot be used in its original format because it is not convenient to store and therefore it is not widely accepted by commercially available CAD systems. Thus, some scanning systems have provided with standard software and interface for data editing. In some application environments such as the virtual-try-on and MTM, it is not possible or efficient to use such large amount of data, e.g. the full body model corresponds to about 5 Mbytes of data, since it needs a very powerful hardware for processing. Therefore, data compression or modeling plays an important role for reducing problems in data transfer and storing. Moreover, once a different sized body is required, a real human body of that specific size has to be scanned and the whole body model building process has to start over again [4, 5]. Some researchers has been working on the parametric body model [4] for new approaches to build the 3D body model from a 3D body scan data, which can integrate with CAD and CAM software.

However, the 3D scanning methods have failed to overcome two critical problems. First, the extremely expensive cost of the equipment [6] prevent it from wide applications in garment industry. Second, the data format either in the original point clouds or simplified mesh models is not easily to be linked to a parametric model, which can be automatically modified to different shapes by the user parameter inputs [7, 8]. It supports too many dimensions so that the tailor sometimes feel puzzled because for traditional custom-made clothing based to the manual measurements, the tailor usually only need to measure a set of key dimensions.

For this reason, this paper intended to build a parametric human body model, which can represent an individual body by inputting some key dimensions which is more than the traditional manual measures but drastically fewer than the 3D body scanner data. This paper addresses the following research problems: (1) what parameters to be used to describe a human body shape effectively? (2) how to construct a body model based on these parameters? This parametric human body model is a fundamental for the downstream digital apparel product design and evaluation such as virtual try-on and automatic made-to-measure. The human body model consists of two layers: the skeleton and the cross-sections of each body part. The contributions of this paper are as follows. Firstly, a simple skeleton model with the body scanner $[TC]^2$ system has been improved through adding and adjusting the position of joints in order to better address some fit issues related to body shape changes such as spinal bending. Secondly, an automatic approach to extracting semantic features for cross-sections has been developed based on the body hierarchy. For each cross-section, it is described by a set of key points which fit a closed cardinal spline to the cross-section for each body part. According to the unique distribution of cloud points for each cross-section of each body part, the extraction method of key points on the cross-section has been studied and developed. Thirdly, an interpolation approach is presented to fit the key points on a cross section to a cardinal spline, in which different tension parameters are tested and optimized to represent simple deformations of body shape. Finally, a connection approach of body parts is proposed by sharing a boundary curve. The created human body model in the virtual human model (VHM) system can be imported in CAD environments for a wide variety of ergonomic analysis applications.

The paper is structured as follows. In the next section, the related works on virtual human body modeling and method are discussed. The human body model is defined in the section 3 and the detail method for constructing human body model is presented in section 4. Section 5 reports the implementation of the algorithm and shows some examples before the conclusion.

II. Related Work

Along with the evolution of human-centered product design processes, there have been many techniques for human body modeling in the literature. These models can be typically classified into five categories: (1) Soft tissue model, (2) 3D body scanning model, (3) Implicit model, (4) Statistics-based model and (5) Parametric body model.

(1) Creative soft tissue model

The goal of anatomy-based method [9, 10] is to build a human model that is as accurate as possible. These models can simulate underlying muscles, bones, and tissues, which are proved to be effective in simulating human body dynamics and complex collisions. However, these methods are not suitable for using in garment CAD systems because they require too much knowledge on human body structures and expertise in computer graphics [6] when modeling the inner structures, which are not of interest.

(2) 3D body scanning model

D'Apuzzo [3] reviewed the existing market usage of 3D human body scanning and proposed that virtual-try-on and virtual-make-over have become possible for fashion and apparel industry. In anthropometric sizing surveys and prediction that need collecting a lot of body measurements from thousands of samples, 3D body scanner systems is prior to the traditional manual measurement because of its short scanning time, high measuring accuracy and high measuring consistency. Moreover, it offers the reusability of data because that the scan data actually replace the 3D human body, which is convenient to gather other additional information. There is no doubt that 3D body scanning methods [7, 11, 12] are very accurate ways of obtaining a human body model. Based on a subdivision surface representation, an effective body modeling algorithm is presented which is for a two-view body scanner. In general, current 3D scanning methods have failed to overcome two critical problems: the extremely expensive cost of the equipment [6] and uneasy to be linked to a parametric model.

(3) Implicit model

The implicit surface methods describe human models as level sets of a scalar field. Xiao and Siebert [13] proposed a modeling scheme, in which each human body part is fitted into a quadric primitive. The method is fully automatic and involves the HBS data segmentation reported in [14]. However, because of their considerable requirements in human interventions and calculations, implicit surface is difficult to model and animate interactively [15]. Furthermore, they cannot deal with human shape details accurately.

(4) Statistics-based synthesis model

Statistics-based synthesis methods build human body models based on the study of the body shape distribution [16]. They collect 3D human face scan data and capture the shape variation by analyzing them with principal component analysis. Some researchers [17-19] applied this approach to a set of 3D human body scan data by fitting template meshes to the target raw data for ensuring a consistent mesh topology. However, these methods can't make the synthesis model as a true parametric one to support an interactive human body modeling [4] for apparel industry.

(5) Parametric body model

The parametric modeling method can be typically classified as two classes: example-based parametric body modeling and feature-based parametric body modeling. The example-based parametric body modeling technique [8, 11, 16] , which fit parametric surfaces to the point cloud, is a good alternative to tackle these shortages of creative soft tissue model and implicit model. Cordier et al. [20] reviewed the body of research work undertaken in the area of example-based modeling and innovative applications in the online clothing design system. NURBS surfaces are most usually adopted, which are best suited for describing body shapes with prescribed topological type [21]. However, this is created at the expense of the computational cost. In the feature-based parametric modeling domain, object semantic features can be systematically described for a given application domain [22]. In apparel design, building semantic features on a human model is paid more and more attentions [23]. A method [24] extended the example-based parametric modeling to the feature-based parametric modeling. They proposed a more advanced technique for modeling human body by finding the correlations between the body sizes and the body models. Following the feature recognition approach, which recognizes various features from a geometric model of an object according to the feature templates defined in a feature library, Wang [22] proposed an angle-based method to sample key points on a cross-section. In their approach, angels are equal, which consists of a contour center and other two end points on a cross-section. However, it is easy to conclude that some sampling problems can come up on the curves with high curvature. An automatic approach to match correspondences on 3D human bodies in various postures was presented, so that feature points can be automatically extracted [25]. This method can further shorten the time of product design and fabrication cycle as a preprocessing step of volumetric parameterization for design automation.

In summary, for supporting virtual garment design, creation of a parametric human body model is necessary. However, current parametric human body models either from example-based or feature-based methods still lack of good links to hand measurable body sizes. They are good for virtual-try-on and other applications, but still not very good for evaluation of individual fitness. There is a need for a better parametric human body model. On the one hand it can describe individual body accurately and on the other hand it has a few parameters which are not only able to describe a human body based on main body dimensions but also able to describe some small changes of each body part. In addition, these parameters can be easily linked to a small set of hand measurable body sizes. This will enable a better virtual-try-on and a better fitness evaluation based on an individualized body model from a customer's input.

III. NEW HUMAN BODY MODEL

Our purpose of constructing a parametric virtual body model is to meet the above application requirements. Creating a parametric model based on key body dimensions is a similar process to traditional tailors'. They imagine their customers' body shape by some sizes obtained from manual measurements on their body and then design garment for them. Fig. 1 is a process diagram for building the parametric human body, which consists of three modules: 1) modeling module, 2) training module and 3) application module. This paper mainly focused on the modeling module to develop the parametric human body model as shown in the Step 1. Creation of a parametric feature body model is the basis for parametric human body models from dimension parameters. In this step 1, a parameter space can be obtained, which consists of a set of key parameters, to represent body model. This parameter space is different from both the manual measured dimensions required for clothing design and the 3D body scanner data. Next, the relationship between the parameter space and key body dimensions (commonly used manual measured body sizes for clothing design) can be established by a surrogate model which can be trained with parameters in the parameter space and the corresponding key body dimensions, as shown in the Step 2. Finally, once the surrogate model is obtained, inputting some key dimensions into the surrogate model will produce a set of parameters for a parametric feature model, which will produce an individual body model for both garment design model, as shown in the Step 3.

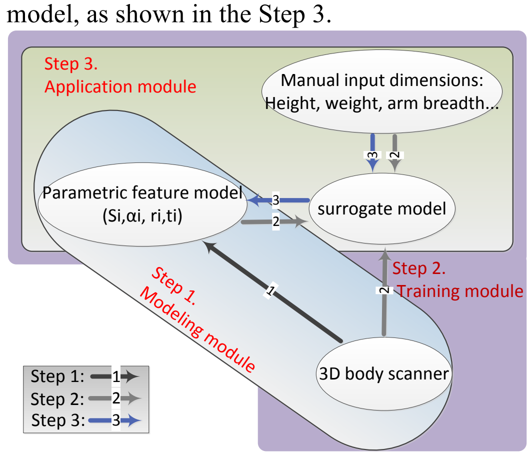


Fig. 1 Diagram for building parametric human body

Generally, if a human body model is used for animation and deformation, it needs to be segmented into sub-parts (head, torso, arms and legs) and then use the skeleton to drive the model deformation. Here, the purpose of building a human model is for virtual try-on and automatic made-to-measure apparel design, in which the human model is required for changing different postures to feel how fit the garment is. Therefore, each body part of the model is constructed separately, and then join them together with constraints. For this reason, this paper proposes a human body model with two layers: the skeleton and the cross-sections of each body part. In order to better address some fit issues related to body shape changes such as spinal bending, firstly, a simple skeleton model embedded in the body scanner $[TC]^2$ system has been improved by adding and adjusting positions of joints (see Fig. 3(c)). The human body is driven by a skeleton consisted of 20 joints as shown in Fig. 3(c).

In summary, for building a parametric human body, it firstly needs the skeleton construction, and determines the relative positions of cross-section for each body part, the polar representation of the key points, and the tension parameters. Next, it needs to establish the relationship between the parameter space and key body dimensions by a surrogate model. Once the surrogate model is built, inputting some key dimensions into the surrogate model will produce a parametric body model for both garment design model. This paper focused on the first part.

IV. New Method

Our virtual human body modeling process is shown in Fig.2. 3D body scanning data come from the NX-12 3D body scanner by TC^2. In this system, a scanned human body is in its standing posture facing the screen as shown in Fig. 4(a). The raw scanning data is point clouds, from which joint data can be extracted. The system can also automatically segment human body model into eight major parts: head, torso, two arms, two legs and two hands, as shown in Fig. 4(a). It can be obviously seen that the segmentation is not very good, the arm data and torso data are partly overlapping, and the head is not separately segmented.

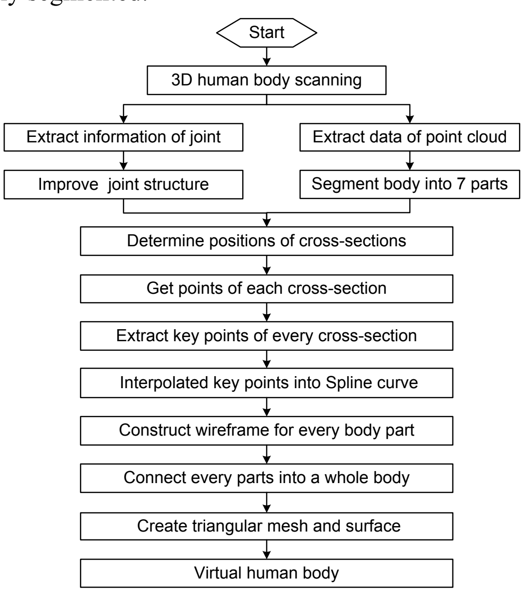
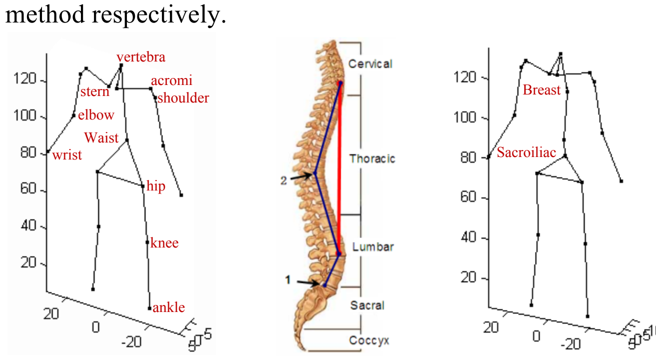


Fig. 2 Construction process of human body model

A. Skeleton construction

Soft tissue simulation is central to the process of creating realistic character animations. However, these human models and simulations are constructed at the expense of time consuming and computational cost. By contrast, in garment design environments such as virtual-try-on and automatic made-to-measure, users and designers generally just need a few simple postures of body model to demonstrate their products. In this paper, the goal of skeleton construction is to segment the human model into several body parts, such as neck, torso, arms and legs, so as to construct parametric structure separately for each body part. Also the skeleton construction offers convenience to the deformation and animation of a parametric human body model in due course.

To create the skeleton, firstly the joint data from the 3D body scan system is exported shown in Fig. 3(a). A lateral view of the spine illustrates the regions and naturally occurring curves, as shown in Fig. 3(b). The joint construction obtained by the body scan system is too simple to express the spine structure as shown in red line in Fig. 3(b). However, it is one of the most important elements for automatic made-to-measure because spine structure can reflect the body shape such as humpback. For this reason, this joint construction is then improved by adding two new joints in the torso part, as shown in blue line in Fig. 3(b). Comparing the spinal columns from this Fig. 3(b), it is not difficult to see the spinal column obtained by our method is better to approach the human body skeleton construction, allowing body bending around the point 2 in Fig 3b. The improved joint construction is very important for virtual garment design, and very convenient to describe the upper body shapes associated with the spine structure. A bone is finally obtained by linking two specified joints, in other words, two adjacent bones are linked on a joint. Fig. 3(a) and (c) shows the two skeleton constructions from the 3D body scanner and the improved method respectively.



(a) body scanner method (b) side of spinal column (c) the improved method
Fig. 3 Skeleton constructions

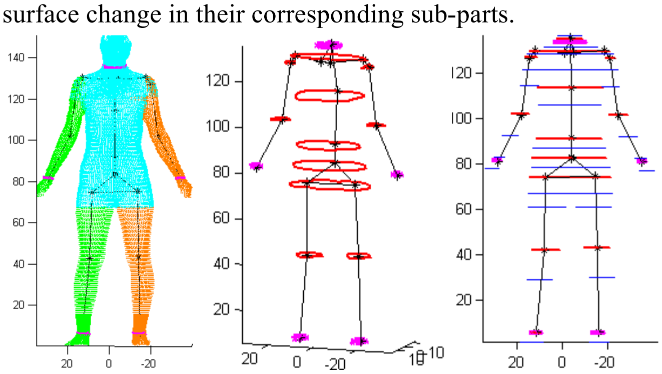
B. Cross-section construction

Generally, human animation or deformation methods require a human model to be segmented into head, torso, arms and legs and so on. Therefore, a wire frame of each part is constructed separately, then join them together with constraints. For each body part, its wire frame model is built in four steps: 1) determine the positions of cross-sections on each part, 2) extract key points on cross-sections, 3) interpolate the key points into contour curve, and 4) connect each body part into a whole body wireframe structure.

1) Semantic determination of positions of cross-sections

The approach for automatic determination of the positions of cross-sections is hierarchy-based and can be summarized as the following three steps. Firstly, extract three key joints: the vertebra joint, wrist joints and ankle joints, as shown in Fig 3(a) and (c), and then insert three horizontal planes through these joints to separate the human model into six major portions: head, arm-torso-leg, two hands and two foots, as shown in Fig. 4 (a). The intersections between these planes and the scanned body result in five category I cross-sections (shown in pink in Fig. 4(a)). The key portion (arm-torso-leg) bounded by these cross-sections consists of the arms without hands, the torso and the legs without feet. It is the most important portion for us to develop the automatic made-to-measure model.

Secondly, in the arm-torso-leg portion, extract the following joints: bust joint, waist joint, hip joints, knee joints and elbow joints, as shown in Fig. 4(a) and (c). Inserting corresponding horizontal planes through those joints can further subdivide the human body into several sub-parts by eleven category II cross-sections (shown in red in Fig. 4(b)). Finally, twenty five category III cross-sections (shown in blue in Fig. 4(c)) are located in sub-parts with anthropometric semantics, including crotch point, mid-thigh point, calf point, neck point, under bust point and so on. These feature points reflect the major surface change in their corresponding sub-parts.



(a) category I (b) category II (c) category III

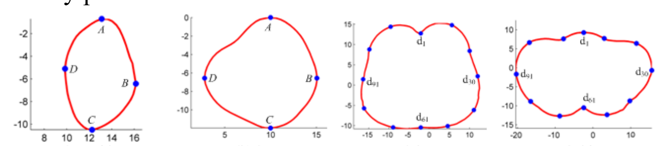
Fig. 4 Semantic feature Cross-section

For garment design, some cross-sections are selected from the three categorized cross-sections to separate the human model into six major parts: neck, torso, arms and legs, as shown in Fig. 4(a). The leg and torso parts are connected at the cross-section through crotch point; the torso part and the neck part are connected at the cross-section through the neck point. Because the shoulder complex involving the arm and the torso parts is very difficult to segment by a single cross-section, so a new strategy is adopted based on some key points to slice it which will be detailed in the section 4.3.

2) Key points

From Fig. 4(c), it can be seen that a human body can be simply represented by the set of cross-sections. But each cross-section still contains a mass of raw data. In order to create a controllable human body model, some key points on each cross-section need to be extracted to further compress these raw data, and then fit these key points to a spline curve for preferably controlling these cross-sections.

To approximate cross-sections well and simultaneously create high quality triangulation meshes of a body model, this paper extracts key points on cross-sections for interpolating curves as follows. The key points of each cross-section excluding torso's and neck's sections are defined as the extreme points which represents the highest point A, lowest point C, the far left point D and far right point B in the raw data, as shown in Fig. 5(a) and (b). It is complicated for setting out rules to extract the key points on the torso and neck parts and therefore, the key points on these parts are identified from their index in scanned data, which are based on observation and statistics. Firstly, according to the near symmetry of torso and neck parts, the first point (d_1) and the middle point (d_{61}) in the raw data list $\{d_1,d_2,\ldots,d_{120}\}$on each cross-section are defined as key points, as shown in Fig. 5(c) and (d). They segment a cross-section into two sub-parts. Next, according to the same distribution of raw data on cross-sections, points (d_{11}, d_{21}, d_{30}, d_{41} and d_{51}) and points (d_{71}, d_{82}, d_{91}, d_{101} and d_{111}) are defined as key points. Fig. 5 shows the key points extracted on some cross-sections.



(a) ankle (b) knee (c) bust (d) hip

Fig. 5 Extracted key points on cross-sections for female

Our method can obtain well-proportioned key points on each cross-section, as shown in Fig. 5. The statistic knowledge is adopted to extract the key points based on the regular distribution of raw data on the cross-sections, and then to determine the ordinal numbers of key points in the sequence of raw data, Compared to angle-based method and length-based method for decomposing a cross-section, this method avoids the problem of under sampling on the parts with high curvature, and improves the shape quality of triangular meshes formed with these key points.

3) Interpolation and Optimization

We interpolate more points, which are called as interpolation points, between two adjacent key points on a cross-section to approximate the raw data, and meanwhile make the human model more controllable. The number of interpolation points is controllable and can determine the body surface quality. A cardinal spline, a sequence of individual curves joined to form a larger curve, is used to represent each cross-section in the interpolation method. If takes $P_i(u)$ as the representation of the i^{th} cross-section, the $P_{i,k}(u)$ to represents a segment between key point $p_{i,k}$ and $p_{i,k+1}$ as shown in (1). The four control key points from $p_{i,k-1}$ to $p_{i,k+2}$ are used to set the boundary condition for a cardinal spline section as in (2).

$$P_{i,k}(u) = \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \times Mc_i \times \begin{bmatrix} p_{i,k\text{-}1} \\ p_{i,k} \\ p_{i,k+1} \\ p_{i,k+2} \end{bmatrix} \tag{1}$$

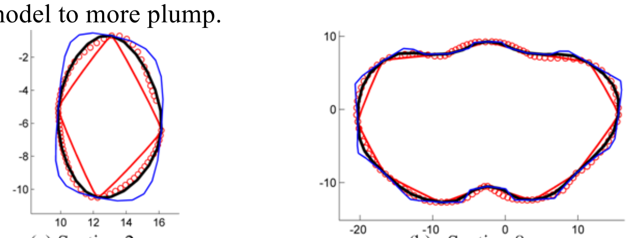
where the cardinal matrix is

$$Mc_i = \begin{bmatrix} -s_i & 2-s_i & s_i-2 & s_i \\ 2s_i & s_i-3 & 3-2s_i & -s_i \\ -s_i & 0 & s_i & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

with $s_i = (1\text{-}t_i)/2$. Parameter t_i is called the tension parameter that can reflect the body shape of plump and lean. The boundary conditions that define the cardinal spline section are

$$\begin{cases} P_i(0) = p_{i,k} \\ P_i(1) = p_{i,k+1} \\ P_i^{'}(0) = (1-t_i)(p_{i,k+1} - p_{i,k-1})/2 \\ P_i^{'}(1) = (1-t_i)(p_{i,k+2} - p_{i,k})/2 \end{cases} \tag{2}$$

Cardinal spline is used in interpolating human body model for three reasons. Firstly, this spline is specified by an array of key points on a cross-section with one or more tension parameters. It passes smoothly through each key point in the array so that there are no sharp corners and no abrupt changes in the tightness of the curve. Secondly, cardinal splines don't need input of the values for the endpoint tangents and its slope at each key point is calculated from the coordinates of two adjacent key points. Thereby, this attribute can ensure that two adjacent interpolation curve sections are correlation. Finally, different values for the tension parameter will produce different curves through the same set of key points. Fig. 6 shows four cardinal splines passing through the same set of key points with different tension parameters. It is obvious that a tension parameter of -0.4 is better to approximate the raw point on the cross-section. And the tension of 0.8 changes the body to more lean and the tension of -1.6 creates the body model to more plump.



(a) Section 2 (b) Section 8

Fig. 6 Interpolation curve in different tension parameters: the raw data (red circle); t_i=0.8(red line); t_i=-0.4(black line); t_i=-1.6 (blue line)

In the same way, this paper interpolates more points between two corresponding key points on the adjacent feature cross-sections along the skeleton in each part to construct the wireframe of each body part, and to make the human model more controllable. Those points can form a set of new cross-sections called as assistant cross-sections. The number of interpolation points is also controllable and can determine the body surface quality. The cardinal spline is used to represent the body shape along the skeleton as well.

In this paper, a least squares method for optimizing interpolation curve by tension parameters is proposed. Expanding the matrix (1) into polynomial form, the following equation can be obtained

$$\begin{aligned} P(u) = {} & p_{k-1}(-su^3 + 2su^2 - su) + p_k((2-s)u^3 + (s-3)u^2 + 1) + \\ & p_{k+1}((s-2)u^3 + (3-2s)u^2 + su) + p_{k+2}(su^3 - su^2) \end{aligned} \tag{4}$$

where k=1,2,…n, and the n is the number of sub-parts on the i$^{\text{th}}$ cross-section.

To control the fitting error, the user can initialize the tension parameters and then the system can automatically compute the optimal fitting curve by minimizing the following equation with a tension parameter:

$$Min_t \sum_{i=1}^{n} \| P(u) - q_i \|^2 \tag{5}$$

where q_i is the coordinate position of a raw point nearest to the interpolation curve and t is the tension parameter in (1).

C. Part connection

After creating the interpolation curves on each body part, it is easy to construct a wireframe model for each body part. However, one technical challenge is to properly connect the neighbour parts to torso including arm, neck and leg, where the cross-sections with different shapes meet together. This paper handles this problem by sharing a boundary curve between two neighbour parts. This approach of sharing a boundary curve can be divided into two steps: the reselection of key points on the correlated cross-sections and the construction of the sharing boundary curves.

It is obvious to find that the boundary curves between the neck and the torso parts are identical because the key points are selected in the same rule. For constructing the sharing curve linking the leg (right or left) with the torso, their boundary curves around the hip are similar. Therefore, the key points (See Fig. 7) on the cross-sections of two legs are selected as the sharing boundary points of torso; however, they need to be rearranged according to the distribution of the key points on the torso part. Fig. 7 shows three sections. S_{33} and S_5 are the lower sections for right and left legs, S_{34} and S_6 are the middle sections near to the hip position, and S_8 is the upper section for the torso. Modifying S_{34} and S_6 into S_7 will make it easier to connect with S_8. Because of the different numbers of key points on S_7 and S_8, adjusting the number of interpolating points for each cross-section is needed to make them with the same number of key points for connection.

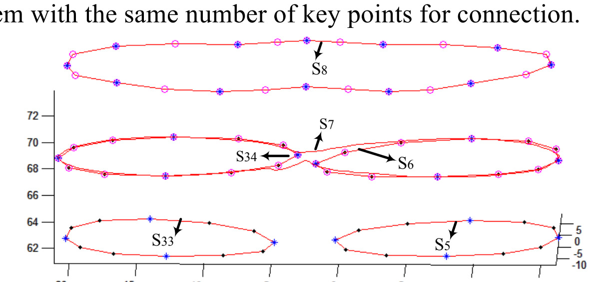
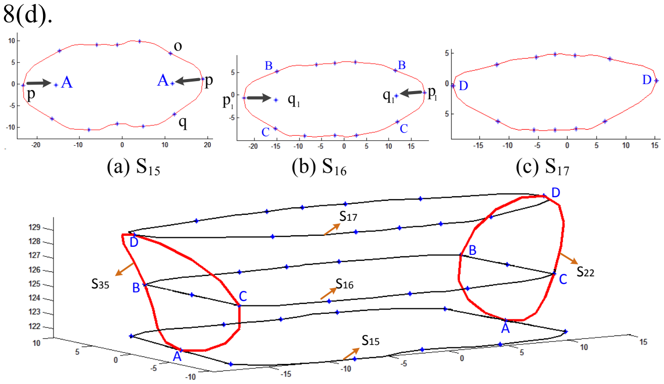


Fig. 7 Key points of the sharing boundary curve for legs and torso

It is the most difficult to obtain the sharing boundary curves for combing arm part and torso part because they aren't on the same plane. The key points need to be reselected for interpolating a sharing boundary curve which belongs to both arm part and torso part. The constructing method is discussed as follows. Firstly, the position of key point (p) on the cross-section (S_{15}) is adjusted to the position (A) which is the average of the neighbour key points (o and q) of key point (p), as shown in blue star in Fig. 8(a). The key point (A) is selected as a key point of the sharing boundary curve. Secondly, other two key points (B, C) on the cross-section (S_{16}) of torso part are selected as the key points of their sharing boundary curve, and the key point (p_1) is adjusted to the position (q_1) which is the average of the neighbour key points (B and C), as shown in Fig. 8(b). In this way, the key point (D) on the cross-section (S_{17}) of torso part is selected as a key point for their sharing boundary curve, as shown in Fig. 8(c). Finally these new key points are sorted in accordance with the sequence of the key points on the cross-section of arm part. For avoiding model intersection between torso and arm parts, the boundary condition of cardinal curve on these adjusted key points is revised so that the related cardinal curves become line segments across the section, as show in Fig. 8(d). The new cardinal curves (shown in black) are fitted by the new key points on the cross-sections (S_{15}, S_{16}, S_{17}) of torso part with adjusted boundary conditions and the cardinal curves (shown in red) are the boundary curve of the arm part, as shown in Fig. 8(d).



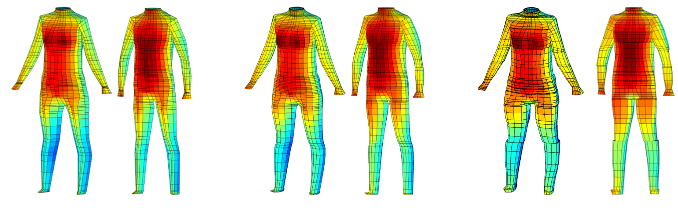
(a) S_{15} (b) S_{16} (c) S_{17}

(d) Allocation plan of key points

Fig. 8 Key points of the sharing boundary curve for arms and torso

V. IMPLEMENTATION AND APPLICATIONS

This virtual human model (VHM) system has been implemented on Windows XP by using MATLAB (R2011a). The input data is from the NX-12 3D body scanner by $[TC]^2$. Firstly, it extracts the joint data from the point cloud and then improves the joint data and compresses the scanned body point cloud into the parametric virtual body model presentation. Finally, this system obtains the wireframe construction by interpolation. It is easy to describe a human body model with small variations on each part by modeling each cross-sections of the body part with difference tension parameters as shown in Fig. 9. The body mesh model can be saved in the STL format. Therefore, it is convenient to export the human model to other CAD systems.



(a) t_i=0.8, t_j=0.8 (b) t_i=-0.4, t_j=-0.4 (c) t_i=-1.6, t_j=-1.6

Fig. 11 Body model for female and male with different tension parameters

At least two direct applications might benefit from the technology including dimension extraction and 3D apparel design. Firstly, the dimensions of the human model and made-to-measures can be obtained easily from the feature cross-sections on the virtual human body model. Table 1 gives a comparison of some dimensions extracted from a 3D body scanner and the virtual human model (VHM). Secondly, the virtual human body model can allow garment designers to design patterns directly on a virtual 3D human body model [26]. This model has parameters linked with clothing design related body sizes, which enables this model not only for simulation of 3D garment result such as a virtual try-on, but also 3D clothing design on a specific virtual human model. Therefore, it has a potential to easily check whether the clothing is fit to the user at different postures in a virtual environment.

Table 1 Comparison of the dimensions extracted from the $[TC]^2$ scanner and the VHM for male and female

	Girth	3D scanner	VHM	Error	Relative error
Female (IDF05)	Bust	91.27	92.04	-0.77	0.844%
	Hip	102.92	102.28	0.64	0.622%
	Waist	81.11	81.05	0.06	0.074%
	Thigh	59.67	59.36	0.31	0.520%
	Calf	36.07	36.38	-0.31	0.859%
Male (IDM37)	Chest	104.83	103.9	0.93	0.887%
	Hip	104.8	104.2	0.6	0.573%
	Waist	93.18	93.03	0.15	0.161%
	Thigh	57.8	57.67	0.13	0.225%
	Calf	36.59	36.47	0.12	0.844%

VI. CONCLUSIONS

This paper presents a new method for modeling human body shape from 3D body scanning data for garment development applications such as clothing design, virtual try-on and made-to-measure. This paper developed an improved skeleton model which can provide important information for testing the fit level of digital apparel to a virtual body. Cardinal interpolation curves are adopted to approximate the cross-sections and use the tension parameters to handle some small variations of body parts. This virtual human model (VHM) system can export a body model into other CAD environments for a wide variety of applications such as personalized avatars. The work described here is the first part of the whole research on clothing design with parameterized virtual human body model, attempting to address the fit issues effectively in the early design stage. The parameterized human body model is the foundation for the downstream clothing design applications. The future work is to develop a direct link between the parametric human body model and sizes for clothing design so as to discard the dependence on 3D body scanners.

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