A new method to evaluate the dynamic air gap thickness and garment sliding of virtual clothes during walking

Abstract

With the development of e-shopping, there is a significant growth in clothing purchases online. However, the virtual clothing fit evaluation is still under-researched. In the literature, the thickness of the air layer between the human body and clothes is a dominant geometric indicator to evaluate the clothing fit. However, such an approach has only been applied to the stationary positions of the manikin/human body. Physical indicators such as the pressure/tension of a virtual garment fitted on the virtual body in a continuous motion are also proposed for clothing fit evaluation. Both geometric and physical evaluations do not consider the interaction of the garment with body e.g. sliding of the garment along the human body. In this study, a new framework is proposed to automatically determine the dynamic air gap thickness. First, the dynamic dressed character sequence is simulated in a 3D clothing software via importing the body parameters, cloth parameters and a walking motion. Second, a cost function is defined to convert the garment in the previous frame to the local coordinate of the next frame. The dynamic air gap thickness between clothes and the human body is determined. Third, a new metric called 3D garment vector field (3DGVF) is proposed to represent the movement flow of the dynamic virtual garment, whose directional changes are calculated by cosine similarity. Experimental results show that our method is more sensitive to the small air gap thickness changes compared with start-of-the-arts, allowing it to more effectively evaluate clothing fit in a virtual environment.

Keywords

Dynamic air gap thickness, garment sliding, body-clothes interaction, 3D garment vector field (3DGVF), and dynamic clothing fit

1. Introduction

Traditional clothing fit evaluation requires the consumer to wear the real garment and walk a few steps to determine if it is a good fit. However, such an evaluation method cannot be used for online shopping. In order to virtually analyze garment in 3D, Garment CAD is designed to simulate realistic clothes [Liu et al. 2010]. A set of famous CAD platforms, such as CLO 3D and OptiTex, are available in the clothing industry for virtual garment try-on. The main challenge of evaluating dynamic clothing fit is that it depends on a number of factors, including clothes-body proportions, fabric material properties, garment designs, and human motions. Since all the aforementioned factors affect the interaction between clothing and the human body, it is difficult to find the best dynamic clothing fit evaluation method. Moreover, the interaction between the garment and the human body has not been studied in the literature. Body-clothes interaction consists of all the physical relationships such as sliding and collision. In this study, one of the aims is to quantitatively represent the garment sliding during movement. To the best of our knowledge, this work is the first attempt to tackle this problem.

The methods of fit evaluation via garment CAD can be classified into two categories. The first one is the geometrically-based method. In geometry processing, the surface of the virtual garment and the human body is represented by a set of triangles or quads [Botsch et al. 2010]. For each of the vertices of the garment, the closest point on the human body can be found. The distances between them are then used to calculate the signed distance field [Bærentzen et al. 2005], which is called the air gap thickness [Psikuta et al. 2012]. Air gap thickness between the virtual garment and the human body is calculated to represent their spatial relationship. The slice-based method is another popular method to determine this air gap thickness [Lage et al. 2017, Thomassey et al. 2013]. A set of parallel planes cut the meshes of the garment and the human body into a set of cross-sectional pairs, which are considered independently when the garment-body distance is calculated. However, these methods can only be used on the stationary positions of the manikin/human body [Psikuta et al. 2015, Psikuta et al. 2012].

The second category is the physical methods, which represent clothing fit using tension/pressure map and intuitively display the clothing fit [Lee et al. 2013, Yanmei et al. 2014]. Larger tension/pressure indicates that larger relaxation should be added during garment design. Liu et al. further extended the methods into dynamic clothing fit evaluation [Liu et al. 2016]. However, existing physically-based approaches cannot be used to describe the spatial relationship between the garment and the human body. Moreover, neither existing geometrically-based nor physically-based methods can represent the sliding of the garment between the virtual garment and the human body during movement. Quantitatively understanding the interaction and dynamic air gap thickness between the garment and the human body facilitates the development of a new criterion of dynamic fit evaluation.

3D scanning rapidly captures the 3D geometry/shape of a subject. It has been successfully applied to 3D human body reconstruction [Tong et al. 2012, Hu et al. 2017, Hu et al. 2018] and automatic body measurements [Han et al. 2011]. [Frackiewicz-Kaczmarek 2013, Yu et al. 2013] applied 3D scanning to explore the air gap thickness between the garment and the mannequin. Like the virtual garment, the slice-based method [Hu et al. 2018] was used to transfer the triangle mesh into a set of cross sections. For the cross sections cut by the same plane on the garment and body, the distance field is calculated separately to represent the local air gap thickness [Frackiewicz-Kaczmarek et al. 2015]. However, this method cannot be used in dynamic clothing fit evaluation because the position of the garment is shifted during the body movement. There is an individual 3D coordinate for a garment in each frame, making it impossible to evaluate the scalar and directional changes for the garments on two different coordinate systems computed from two different frames. Although [Mert et al. 2018, Nam et al. 2011] explored the air gap thickness via analyzing the separate air gap thickness for different postures of the same person. However, the cross sections need to be calculated separately for each frame, which cannot maintain a consistent garment-body relationship. Moreover, the air gap information computed from these discrete postures are not enough to evaluate clothing fit as the transitions between different postures are also important. To tackle this, a common 3D coordinate means a shared 3D coordinate for multiple individual coordinates. The data in each individual coordinate can be mapped to the common 3D coordinate for direct data analysis such as comparing. With the common 3D coordinate, we propose the concept called 3D Garment Vector Field (3DGVF) to quantitatively represent the scalar and directional changes of the dynamic virtual garment.

3D scanning has been widely used with the development of the consuming depth cameras such as Microsoft Kinect [Khoshelham et al. 2012]. Garment capture system has been proposed based on the RGBD camera [Hu et al. 2017]. However, the work of [Kim et al. 2015, Han et al. 2010] suggested that 3D scanning may not be reliable. The raw data captured from the 3D scanner is a point cloud and its accuracy highly depends on the quality of the devices [Khoshelham et al. 2012]. Post-processing of the scanned data such as de-noising, 3D surface reconstruction, hole filling, simplification and smoothing [Weyrich et al. 2004] may further reduce the accuracy of the data. Until now, the researchers cannot reach a consensus that 3D scanning is fully reliable. Since the air gap thickness depends on the registration of the scanned garment and the scanned human body, it is difficult to achieve good accuracy by directly using 3D scanning approaches. Besides the accuracy, there are also such challenging for applying 3D scanning in this study: (1) the capture of dynamic clothes is still under-researched; (2) no proper representation is suitable for modelling the air gap between the body and clothes via 3D scanning; (3) the cost of clothes capture system is expensive.

Compared to the 3D scanning, the physical simulation does not have the above issues and has a cheaper cost. Therefore, instead of using 3D scanning techniques, in this research, a commercial virtual try-on software is used to simulate the dynamic movement of the garment. 3D clothing software has been validated to be precise for application such as virtual garment fitting for the fashion industry [Song et al. 2015, Kim et al. 2013] and they are demonstrated to be reliable on 3D garment simulation [Mert et al. 2018, Wu et al. 2011]. To the best of our knowledge, there is no explicit simulative analysis to evaluate the sliding of the virtual garment and human body undergoing a movement. Our proposed 3DGVF is the first method to quantitatively analyze the sliding of the virtual garment.

The rest of this paper is structured as follows. In section 2, we describe how we adopt a 3D clothing software to simulate dynamic garment during movement, calculate the correspondences between the garment and human body, determine the common 3D coordinate for dynamic garment, evaluate the dynamic air gap thickness and garment sliding between the virtual garment and the human body. Next, we demonstrate the results of the proposed method in Section 3 and analyze the results in Section 4. Finally, we conclude the paper in Section 5.

2. Methodology

This section presents the methodology of the proposed system. Figure 1 illustrates the overview of our method.

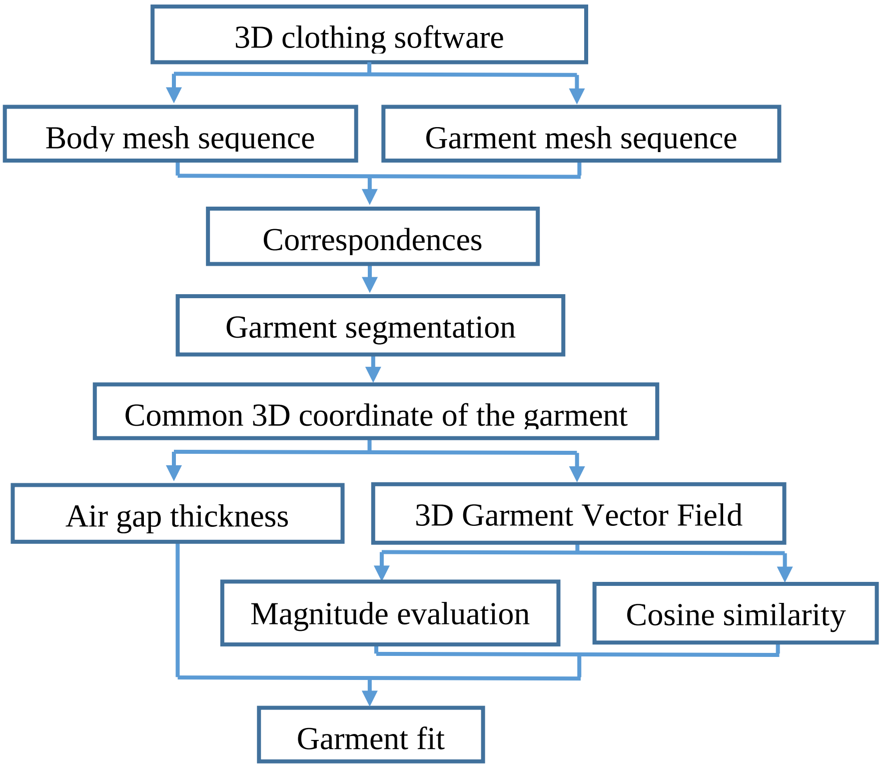


Figure 1 Overview of our method. (a) 3D clothing software is first used to simulate the dynamic garment and to export (b) the body mesh sequence and (c) the garment mesh sequence. (d) Then, the correspondences between the garment and the body are automatically calculated. (e) And the garment is automatically segmented. (f) Next, a new method is proposed to build a common 3D coordinate for the garments in frames. Based on (f), (g) the dynamic air gap thickness is determined, and (h) the 3D garment vector field (3DGFV) is presented to represent the garment sliding. (i) Magnitude evaluation and (j) cosine similarity are used to evaluate the directional and scalar changes of 3DGVF. (k) Finally, the indicator values are compared to explore the fit.

2.1. 3D clothing software

3D clothing software has been developed for modelling of the body and the garment in virtual environments. They normally include three basic modules: 1) a mannequin module to model a human body, which is built using the measurements from a real body; 2) a fabric module to simulate fabric properties; 3) a pattern sewing module to virtually sew 2D patterns together to generate a 3D garment mesh. These modules permit the complete simulation of the process of real garment making. In this study, Clo3D - (http://www.clo3d.com) was used to implement virtual garment try-on. This system was validated to have an accuracy rate of up to 95% based on the measurement of the stretch, bending and other physical properties [Liu et al. 2017]. Real fabrics used in the fashion industry can be converted into virtual fabrics in Clo3D. Motion data can be imported to simulate human movement.

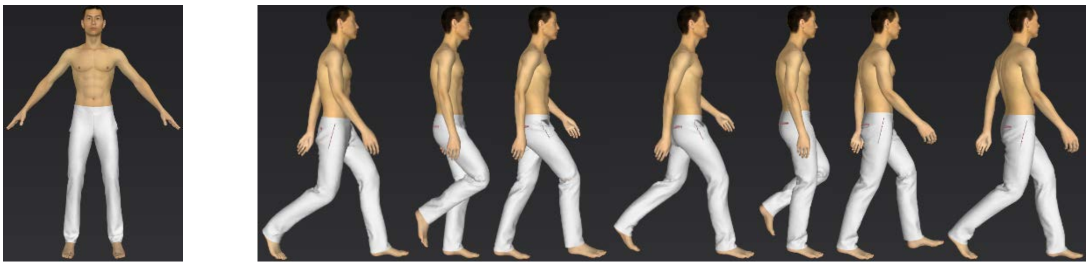
2.2. Avatar and walking simulation

In this study, the body dimensions of a male subject were measured according to ISO 7250-1:2017, as shown in Table 1. These body dimensions were imported into the 3D clothing software to model a virtual avatar. A parametric description of body and arm postures is derived by decomposing the body into serially linked segments according to human anatomic structures. A serial-link manipulator is formed, where every two segments are connected by a joint with one or more rotational degrees of freedom. Subsequently, body postures are described by a relative configuration of the segments, expressed as joint angles. There are 14 joints on the skeleton in this study, as shown in Figure 5. The local movement of a joint is represented via a rotation matrix. Among the joints, one is called the root join which can be translated besides being rotated. The body motion is calculated by multiplying the local joint rotation matrix with the root transformation matrix. A walking motion is imported into the 3D clothing software to simulate a walking human via skeleton-driven animation technology [Baran et al. 2007]. The effects of different motion on the garment fit is not the purpose of this paper. We aim to present a novel method to determine the dynamic air gap thickness and propose a new metric to represent the garment sliding. Hence, the gait pattern is obtained from Clo3D. The surface of the garment will be deformed driven by the surface of the human body continuously via physically-based simulation. Figure 2 shows a cyclic walking motion from the 3D clothing software consisting of 37 frames, which is equivalent to 1.2 seconds. In computer animation, a rest pose, which is typically a T-pose or an A-pose, is necessary for rigging. As the geometry of the garment is calculated based on each frame, the simulation starts from the rest pose to obtain a well-simulated garment. The rest pose can also be used for establishing dense correspondences between the body and the garment, which will be introduced in the following section.

Table 1
Body dimensions of a male person

Abbr.	*BC*	*NWC*	*HC*	*BH*	*UPC*	*LTC*	*KC*	*CC*	*AC*	*CH*	*KH*
Value	*96cm*	*74cm*	*91cm*	*180cm*	*54cm*	*49cm*	*34cm*	*36cm*	*22cm*	*89cm*	*50cm*

Note: **BC** is bust circumference; **NWC** is natural waist circumference; **HC** is hips circumference; **BH** is body height; **UPC** is upper thigh circumference; **LTC** is lower thigh circumference; **KC** is knee circumference; **CC** is calf circumference; **AC** is ankle circumference; **CH** is crotch height; **KH** is knee height



(a) (b)

Figure 2 (a) A snapshot of the rest pose; (b) Snapshots of 7 sampled frames during a walking cycle.

2.3. Fabrics and garments

The mechanical properties of fabric such as stiffness can be translated into the virtual fabrics as well as can influence the result of the physical simulation. However, the analysis of how different mechanical properties of a fabric affect the results of the physical simulation is out of the scope in this research. A frequently used jeans fabric [Liu et al. 2017] is selected to simulate the dynamic virtual try-on. The mechanical properties of the jeans fabric are shown in Table 2.

Table 2

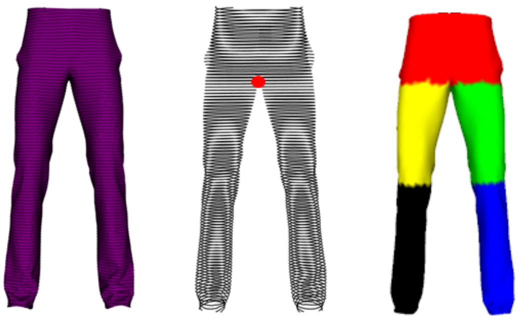
Values of the fabric mechanical properties

Abbr.	*SWT*	*SWP*	*S*	*BWT*	*BWP*	*BRWT*	*BRWP*	*BSWT*	*BSWP*	*ID*	*D*	*FC*
Value	*27*	*27*	*9*	*38*	*38*	*80*	*80*	*80*	*80*	*1*	*27*	*3*

Note: **SWT** is stretch-weft; **SWP** is stretch-warp; **S** is shear; **BWT** is bending-weft; **BWP** is bending-warp; **BRWT** is buckling ratio-weft; **BRWP** is buckling ratio-warp; **BSWT** is buckling stiffness-weft; **BSWP** is buckling stiffness-warp; **ID** is internal damping; **D** is density; **FC** is friction coefficient. The values of these fabric mechanical properties are relative values in the range of 1-99, defined by the Clo3D software.

(a) (b) (c)

Figure 3 (a) Tight-fit pants; (b) Good-fit pants; (c) loose-fit pants.



(a) (b) (c)

Figure 4 (a) Slicing the pants; (b) Determining the crotch point; (c) Segmenting the pants.

Pants are considered in this research as they are one of the most difficult type of clothes to be evaluated [Eccles et al. 2011]. By using an avatar, three pairs of straight pants including good-fit, loose-fit and tight-fit are designed by a fashion expert, as shown in Figure 3. [Psikuta et al. 2012] manually segmented the manikin body into body parts for calculating the air gap thickness separately. In this paper, the segmentation process is fully automatic, and the segmentation is exclusively done on the pants rather than the body. During the stage of establishing correspondences (section 2.4), each garment point v_g finds its closest bone. The pants are segmented into five parts. After that, the crotch point is determined by a slice-based method [Hu et al. 2018]. Specifically, a set of equidistant parallel planes cut the human body into a set of dense cross-sections, as shown in Figure 4 (a). From bottom to top, when the number of cross sections changes from two to one, the crotch point is determined. Using the crotch point, the final segmentation of pants is done as shown in Figure 4 (c).

2.4. Dynamic air gap thickness and garment sliding representation

According to the literature [Psikuta et al. 2012, Lage et al. 2017, Thomassey et al. 2013], air gap thickness between the garment and the human body is an important indicator to quantitatively evaluate the garment fit. However, the slice-based methods of determining the air gap thickness cannot be used in dynamic clothing fit evaluation due to the inconsistency in coordinate systems in different frames. Moreover, the garment sliding between the garment and the human body during movement has not been sufficiently studied. In the area of garment transfer, [Meng et al. 2012, Brouet et al.2012] indicated that using closest body skin points as the correspondences of the garment is not reliable. This is because it can cause points to slide along the body on the target character. We tackle this problem by proposing a novel method to establish the dense correspondences between the garment and the human body. Based on the correspondences, the 3D common garment coordinate for representing garment sliding is determined. When building the 3D common garment coordinate, the local relationship between the virtual garment and the human body is preserved. Finally, a novel method is proposed to determine the dynamic air gap thickness, and a new concept call 3D Garment Vector Field (3DGVF) is proposed to represent the garment sliding between the garment and the human body during movement.

2.4.1. Correspondences

To calculate the air gap thickness, reference points between the garment and the human body should be given first. These reference points are usually sparse and manually marked to establish cross sections at desired positions such as the waist [Thomassey et al. 2013]. We call them the *dense reference points*, representing the closest points between the garment and the human body. Using closest body points as the correspondences of the garment is not reliable as it can cause points to slide along the body on the target character [Meng et al. 2012, Brouet et al.2012]. To overcome the drawback, the following method to determine the correspondences are proposed.

The correspondences are calculated in the rest frame. Figure 5 illustrates the resulted correspondences via our method. It can be observed that the correspondences are so dense that the reader cannot identify the correspondences clearly. Hence, a sampling rate of 20% is used for better visualization. We select 20 percent sampling rate due to the trade-off between visualizing the dense and clear correspondences. For each garment vertex v_g, we first find its closest bone on the skeleton, as shown in Figure 5(a). Then, the closest point v_b can be determined on the closest bone. Since the surface of the human body is in-between the surface of the garment and the skeleton, the segment $[v_g, v_b]$ will definitely intersect with the surface of the human body mesh such that the intersection point v_h is unique. More specifically, the segment $[v_g, v_b]$ will intersect with only one triangle t of the human body mesh. v_h is represented via barycentric coordinates, as shown Eq. (1). w_m represents the weights of the barycentric coordinates, and t_m denotes the vertex position of t. By this, all vertices of the garment can establish one-to-one dense correspondences on the human body, as shown in Figure 5(b). The algorithm of the correspondence can be found below:

$$v_h = \sum_{m=1}^{3} w_m \times t_m \,, where \;\; \sum_{m=1}^{3} w_m = 1 \tag{1}$$

Algorithm 1 Correspondences

Require:

Garment mesh of rest pose $=\{GV, GT\}$,

Body mesh of rest pose$=\{BV, BT\}$,

Bones of rest pose$=\{B\}$

1: For each vertex v_g in GV do

2: **Vector3d** intersection, segment, correspondence

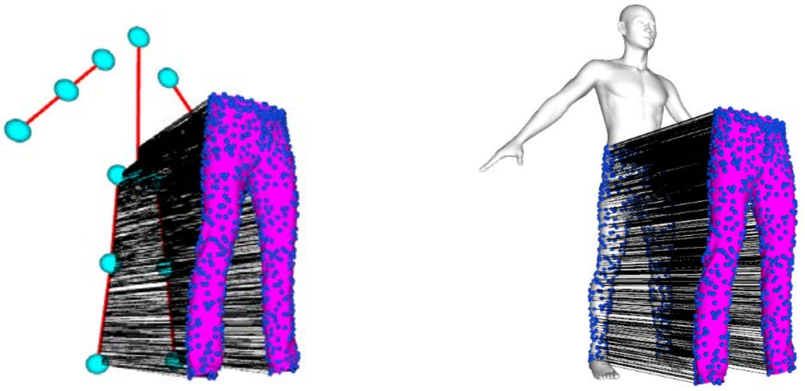
3: Calculate the closest bone b_i for v_g

4: intersection= [calculate the intersection point between b_i and a ray cast from v_g]

5: segment=[v_g, intersection]

6: For each triangle t_z in GT do

7: correspondence=[calculate the intersection point between the segment and the surface of the human body]



(a) (b)

Figure 5 (a) correspondences between the garment and the skeleton (20 percent sampling); (b) correspondences between the garment and the human body (20 percent sampling).

2.4.2. Dynamic Air Gap Thickness

Air gap thickness between the garment and the human body is a conventional dominant indicator to evaluate clothing fit. However, these methods of determining air gap thickness are limited to the stationary poses of the human body/mannequin [Psikuta et al. 2015, Psikuta et al. 2012]. Mean shortest distance fails to calculate the dynamic air gap thickness [Meng et al. 2012, Brouet et al.2012]. The mean correspondence distance is used to calculate the mean air gap thickness for the rest pose frame, as shown in Eq. (2). A_p^j represents the air gap thickness of frame j at part p of the pants, n

represents the number of garment vertices at part p of the pants, ${v_{g}}_{m}{}^{j}(p)$ represents the m^{th} vertex position of garment at part p of the pants in frame j, and c_m^j represents the correspondences on the surface of the human body for ${v_{g}}_{m}{}^{j}(p)$ in frame j. These correspondences are established in the rest pose frame. However, Eq. (2) cannot be used for determining the air gap thickness for the rest of the frames. As the garment slides along the surface of the human body during movement. Hence, the calculated air gap thickness via Eq. (2) will be larger than the real air gap thickness. To solve this issue, the garment of the rest pose frame will be converted to the same coordinate to the rest of the dynamic frames. The local relationship between the garment and the human body will be preserved during the deformation. In this way, the garment of rest frame is converted to the coordinate of each dynamic frame. As illustrated in Figure 6, in one dynamic frame, v is one vertex in the garment in the frame j, c is the correspondence of v on the human body, and v' is the transformed position of v from rest pose frame. Two vectors, V and V' can be determined as:

$$\mathrm{A}_p^j = \frac{1}{n}\sum_{m=1}^{n} dist({v_{g}}_{m}{}^{j}(p), c_m^j) \quad (2)$$

$$V = v - c \quad (3)$$

$$V' = v' - c \quad (4)$$

The projection of V on V' is represented by $pro(V, V')$.

$$pro(V, V') = V \times \frac{V \cdot V'}{\|V\| \times \|V'\|} \quad (5)$$

Then, we use the following equation to calculate the air gap thickness for dynamic frames.

$$\mathrm{A}_p^j = \frac{1}{n}\sum_{m=1}^{n} \|pro(V_m, V_m')\| \quad (6)$$

For calculating the air gap thickness of each dynamic frame, each vector between the paired correspondences in the dynamic frame is projected onto the corresponding vector converted from the rest frame. This will be further explained in detail in the next section.

2.4.3. 3D Garment Vector Field

Dynamic air gap thickness between the garment and the human body is not sufficient to describe the garment movement. The garment sliding between the garment and the human body has not been studied. Compared to the traditional stationary garment fit research, the dynamic garment fit has these challenges:

- The garment slides along the surface of the human body during movement. No existing representation can be used to describe this action.
- The vertex positions of the garment in different frames are in different coordinate systems. A common 3D coordinate system of garments in different frames is necessary for investigating the dynamic garment.
- It is difficult to derive the spatiotemporal relationship between two adjacent frames.

To solve the above issues, a novel concept called 3D Garment Vector Field (3DGVF) is proposed to represent the garment sliding along the surface of the human body during movement. 3DGVF is inspired by the concept of the vector field. Vector field data arises from applications contexts including sensor outputs, flow-field for image analysis, and dataset visualization [Husselmann et al. 2012]. We extend this concept and propose 3DGVF for representing the sliding flow of the dynamic garment. In each frame, the points of pants/body are represented based on an individual Euclidean coordinate. For comparison, it is necessary to map these data from different coordinates to a shared coordinate. If a common 3D coordinate is built to convert the garment in the previous frame to the local coordinate of the next frame, we can build a vector V_m^j by Eq. (7). v_m^{j+1} represents the m^{th} vertex position of the garment in frame $j+1$, and $f\left(v_m^j\right)$ is the converted m^{th} vertex position in frame $j+1$ from frame j. V^j is considered as the 3DGVF of frame j.

$$V_m^j = v_m^{j+1} - f\left(v_m^j\right) \tag{7}$$

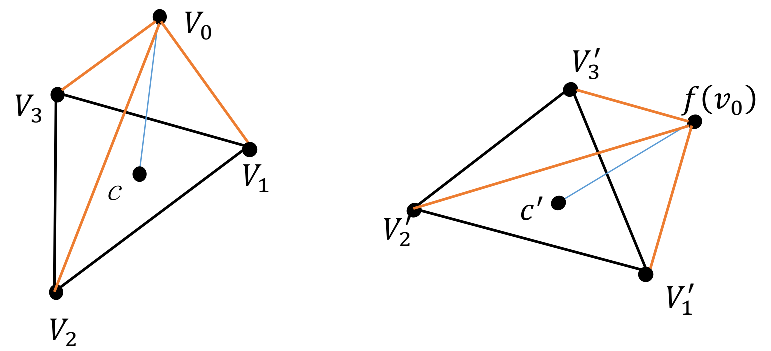


Figure 6 (a) one garment vertex v_0 and its corresponding triangle on the human body in frame j; (b) the transformation of v_0 for frame $j+1$ from frame j.

Since the coordinates of m^{th} vertex position in frame j and frame $j+1$ are different, function f is designed to covert the coordinate in frame j to the coordinate of frame $j+1$. Skeleton-driven animation technologies such as linear blending skinning [Baran et al. 2007] can be used to build f. These methods attach the vertices of the garment and the human body on several corresponding bones of the skeleton and deform the surface of the garment by controlling the joint angles. However, the local relationship between the garment and the human body cannot be preserved. Our solution is inspired by the work of [Sumner et al. 2004]. During the stage of establishing the correspondences, the correspondences on the human body are calculated via barycentric coordinate. Therefore, each vertex of the garment is found by using its corresponding triangle on the human body, which is called local relationship. During mapping the data from one coordinate to a shared coordinate, the local relationship should be preserved. As shown in Figure 6, v_0 represents one vertex of the garment in frame j, $t = [v_1, v_2, v_3]$ represents the corresponding triangle of v_0 on the human body. The key idea of building f is to preserve the local relationship between v_0 and t. Therefore, a tetrahedron $\mathrm{C} = [v_0, v_1, v_2, v_3]$ is rigid. The corresponding triangle in frame $j+1$ is given, represented by $t' = [v_1', v_2', v_3']$. The tetrahedron $C' = [v_0, v_1, v_2, v_3]$ is rigid. A transformation matrix $[r, z]$ exists to meet Eq. (8). f is then built via Eq. (9).

$$v_n' = r \times v_n + z, \qquad n = 0,1,2,3 \tag{8}$$

$$f(v_0) = r \times v_0 + z \tag{9}$$

If we rewrite Eq. (8) to eliminate z, c denotes the correspondence of v_0, we get:

$$v_n' - c' = r \times (v_n - c), \qquad n = 0,1,2,3$$

(10)

Then, Eq. (9) is rewritten as:

$$f(v_0) = r \times (v_0 - c) + c' \tag{11}$$

To calculate the transformation matrix for all the vertices of the garment, a cost function is built as shown in Eq. (12), where T represents the number of vertices of the garment, t_m^j and t_m^{j+1} represents the m^{th} triangle in frame j and $j+1$ respectively.

$$\min_R \sum_{m=1}^{T} \sum_{x=1}^{3} \left(R_m^j \times \left(v_x^j(m) \right) - v_x^{j+1}(m) \right) \tag{12}$$

The l^2-norm of 3DGVF is used for magnitude evaluation. The orientation of 3DGVF will be further explained in the next section.

2.4.4. Cosine Similarity

In this section, the orientation of 3DGVF is evaluated. The cosine-angle coefficient is one of the most popular similarity measures for the correlation between the vectors [Steinbach et al. 2000]. It measures the cosine value of the angle between them. It has been successfully applied to information retrieval applications [Welling et al. 2005] for analyzing text documents. We adopt such an idea into evaluating the directional changes of 3DGVF between adjacent two frames.

We can rewrite Eq. (7) to obtain:

$$\mathrm{V}_m^j = v_m^{j+1} - f\left(v_m^j\right) = Vec_m^{j+1} - Vec_m^j, \qquad where$$

(13)

$$Vec_m^j = \ f\left(v_m^j\right) - c_m^{j+1} \tag{14}$$

$$Vec_m^{j+1} = \ v_m^{j+1} - c_m^{j+1} \tag{15}$$

The cosine-angle coefficient between Vec_m^j and Vec_m^{j+1} is given by:

$$cos_m^j\left(Vec_m^j, Vec_m^{j+1}\right) = \frac{Vec_m^j \cdot Vec_m^{j+1}}{\left\|Vec_m^j\right\| \times \left\|Vec_m^{j+1}\right\|} \tag{16}$$

The cosine-angle coefficient is bounded between 0 and 1. When Vec_m^j and Vec_m^{j+1} are identical, the cosine similarity is exactly one.

3. Results

In the experiments, an avatar was first modeled based on the anthropometric values. Then, three pairs of straight pants including good-fit, loose-fit and tight-fit were designed by a fashion expert. These pants were automatically segmented later. Next, a cyclic walking motion from the 3D clothing software consisting of 37 frames (equivalent to 1.2 seconds) is applied. To validate the proposed method, 3DGVF was first to be calculated to quantitatively represent the garment sliding. Next, we compared the proposed method with state-of-the-art methods of determining the air gap thickness.

Figure 7 (a) illustrates the result of building a common 3D coordinate for frame j from the rest frame. It can be seen that 3DGVF efficiently converts the positions of the garment from the coordinate of the rest frame to the coordinate of frame j while preserving the local relationship between garment and the human body for the rest frame. Based on the common 3D coordinate system, 3DGVF can be defined easily, and its visualization is shown in Figure 7 (b). The tails of the arrows represent the converted vertices of pants in frame j from the rest frame, and the heads of the arrows represent the vertices of pants in frame j. This method can also be used to build a common coordinate for two adjacent frames. 3DGVF offers an intuitive movement flow of the dynamic garment, which provides both scalar and directional changes information.

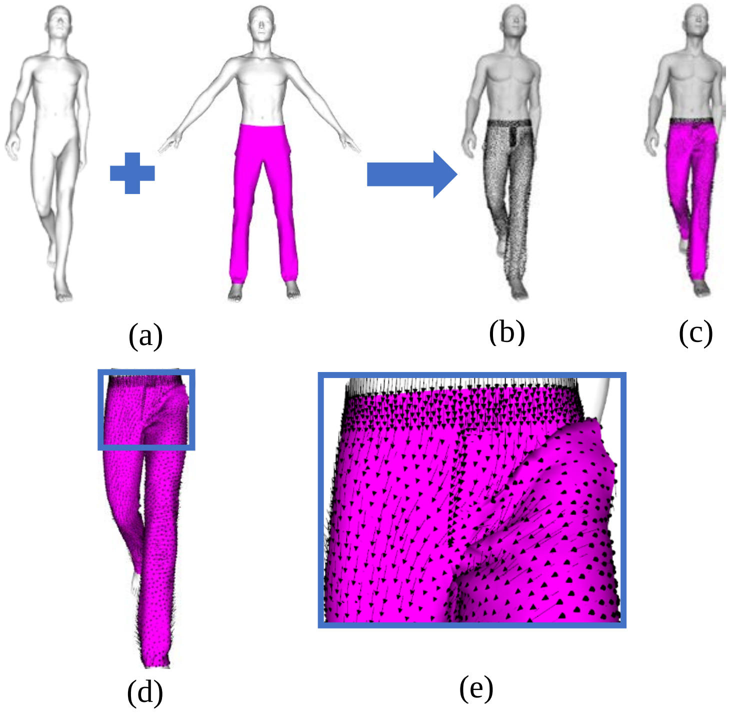
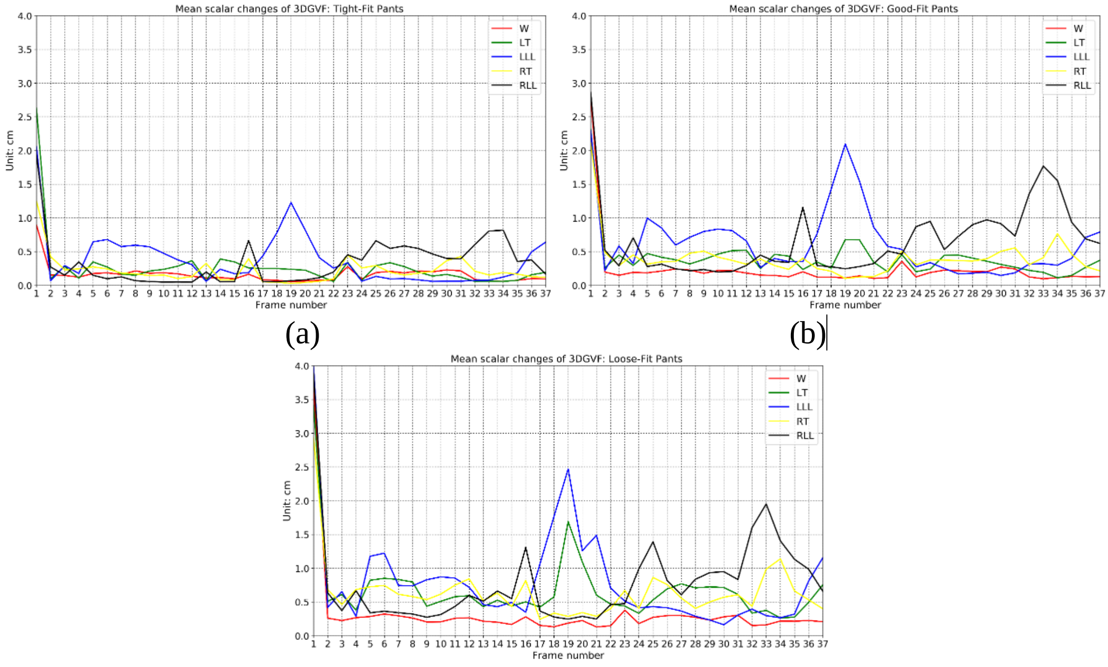


Figure 7 (a) The body model of the 1st walking frame (Frame 1) (left), and the pants and body model in the rest pose frame (frame 0) (right); (b) converting the pants from the rest pose frame to the 1st walking frame (black point cloud); (c) visualizing the converted pants point cloud (black pint cloud) and the physically-based pants (red mesh); (d) building vector fields pointing from the converted to the points of the physically based pants, and denoting the vector fields as 3DGVF to represent the pants sliding in Frame 1 compared to the rest pose frame; (e) close-up of selected part.

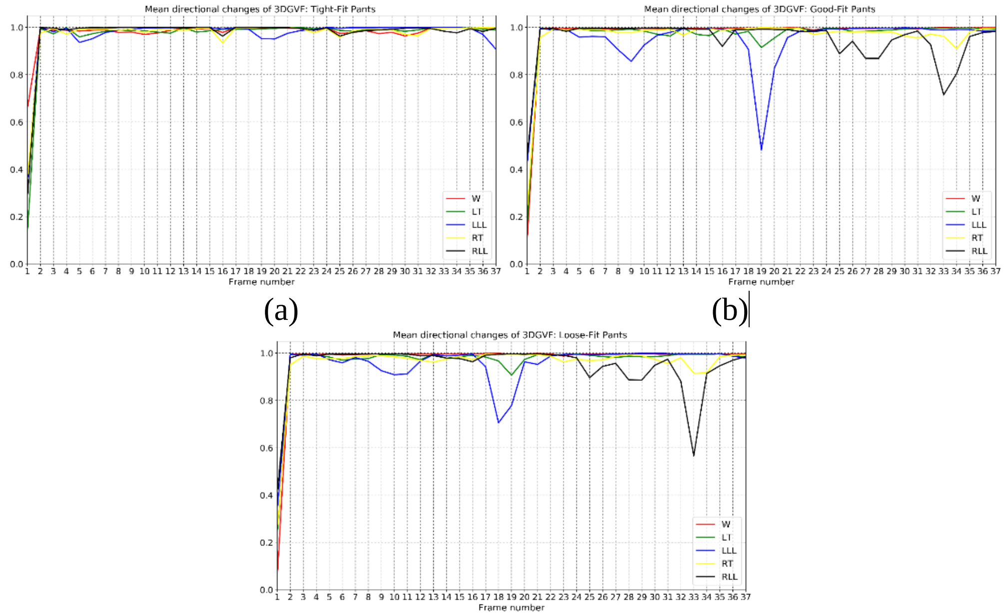
Figure 8 and Figure 9 give the results of dynamic air gap thickness as well as the scalar and directional changes of 3DGVF. As shown in Figure 4 (c), the pants are automatically segmented into five parts. Therefore, the corresponding color of each part is used to draw the curve of the specified part of pants with respect to the frame number. In this study, the walking motion consists of 37 frames (equivalent to 1.2 seconds). It should be noted that our method is suitable for various motions. This is because that the dynamic air gap thickness and 3DGVF are determined by the correspondences only depend on the rest pose frame. Figure 8 and Figure 9 represent the scalar and directional changes of 3DGVF respectively. The data of frame j in Figure 8 and Figure 9 is determined by frame j-1 and frame j. For example, the data of frame 1 in Figure 8 and Figure 9 is calculated by the rest pose frame and the first frame of the walking sequence.



(a) (b) (c)

Figure 8 (a) Mean 3DGVF magnitude of tight-fit pants during walking; (b) Mean 3DGVF magnitude of good-fit pants during walking; (c) Mean 3DGVF magnitude of loose-fit pants during walking.

Note: **W** is Waist; **LT** is left thigh; **LLL** is left lower leg; **RT** is right thigh; **RLL** is right lower leg.



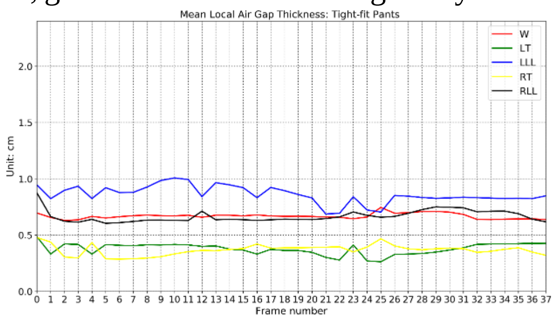
(a) (b) (c)

Figure 9 (a) Mean directional changes of 3DGVF of tight-fit pants during walking; (b) Mean directional changes of 3DGVF of good-fit pants during walking; (c) Mean directional changes of 3DGVF of loose-fit pants during walking;

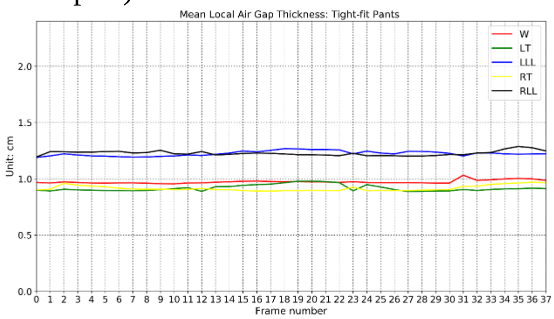
Note: **W** is Waist; **LT** is left thigh; **LLL** is left lower leg; **RT** is right thigh; **RLL** is right lower leg.

4. Discussion

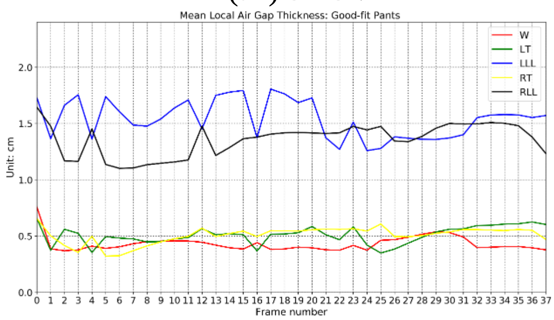
A new method for determining the dynamic air gap thickness between pants and the human body has been proposed and evaluated. Additionally, a novel concept called 3DGVF is proposed to represent the sliding of the garment on the human body surface. The scalar and directional changes of 3DGVF were also measured. All these parameters were measured for five individual pants parts. In the experiments, a 3D model that represents a male subject was animated by a walking motion with 37 frames (equivalent to 1.2 seconds) to evaluate the clothing fit dynamically, and three types of pants (tight-fit, good-fit and loose-fit designed by a fashion expert) were used to validate our method.



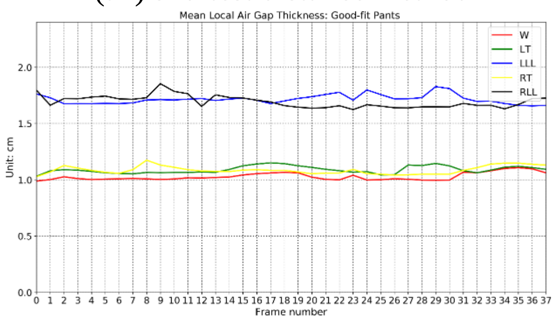
(a1) 3DGVF



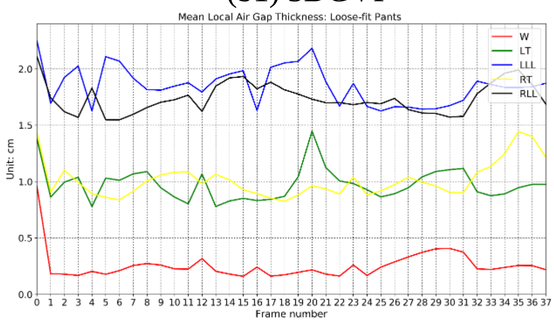
(a2) shortest distance method



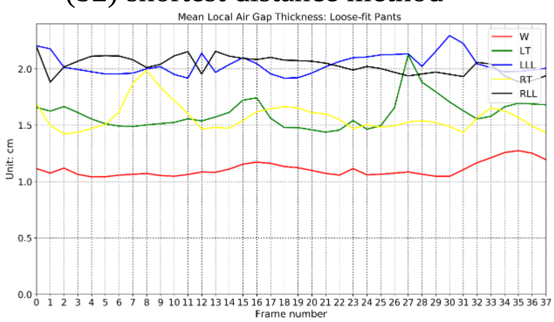
(b1) 3DGVF



(b2) shortest distance method



(c1) 3DGVF



(c2) shortest distance method

Figure 10 Comparing 3DGVF with shortest distance method [Psikuta et al. 2012]: (a) Mean local air gap thickness of tight-fit pants during walking; (b) Mean local air gap thickness of good-fit pants during walking; (c) Mean local air gap thickness of loose-fit pants during walking.

Note: **W** is Waist; **LT** is left thigh; **LLL** is left lower leg; **RT** is right thigh; **RLL** is right lower leg.

Figure 10 compared 3DGVF with the shortest distance method [Psikuta et al. 2012] for determining the local mean air gap thickness during walking. Frame 0 represents the rest frame. As shown in Figure 10, the air gap thickness of dynamic pants fluctuates a lot via 3DGVF, but the air gap thickness of dynamic pants via the shortest distance method is relatively stable. Additionally, it can be seen that the overall values of air gap thickness via the shortest distance method is lower than the values of air gap thickness via 3DGVF. It can also be seen that the red line in Figure 10 (c1) is lower than that in

Figure 10 (b1). Because the loose-fit pants dropped down a bit during walking, the red line of the loose-fit is lower than that of the good-fit. There are two main reasons to explain such differences. The first one is that using the closest points as reference points between the garment and the human body is not reliable [Meng et al. 2012, Brouet et al.2012]; The second reason is that 3DGVF is more sensitive to the changes of air gap thickness in a motion than the shortest distance method. Table 3 further compared 3DGVF with other state-of-the-art methods. Our work is the first attempt to quantitatively represent the garment sliding.

Table 3
Comparing 3DGVF with other state-of-the-art methods

	Tension/Pressure map [Liu et al. 2016]	3DGVF	Shortest distance method [Psikuta et al. 2012]	Slice-based method [Lage et al. 2017]
Stationary air gap thickness	✗	✓	✓	✓
Dynamic air gap thickness	✗	✓	✓	✗
Garment sliding	✗	✓	✗	✗
Garment tension/pressure	✓	✗	✗	✗

As expected, differences in the air gap thickness and garment sliding for tight-fit, good-fit, and loose-fit pants were observed (Figure 8, Figure 9 and Figure 10). The variability of air gap thickness was observed and typically it was approximately in a range of 0.3-1.1cm for tight-fit pants, 0.3-1.7cm for good-fit pants, and 0.2-2.4cm for loose-fit pants. Compared to the air gap thickness of the rest pose frame, the air gap thickness of dynamic pants fluctuates a lot. It can be seen that the air gap thickness of the waist part does not change a lot when the body moves, the air gap thickness of thigh part changes more, and the air gap thickness of lower leg parts changes the most. Compared to the lower legs, the values of air gap thickness in the waist and thighs are lower. For tight-fit pants, the air gap thickness of the waist is close to the range of air gap thickness of the lower legs; for good-fit pants, the air gap thickness of the waist is close to the range of air gap thickness of the thighs; and for loose-fit pants, the air gap thickness of the waist is lower to the range of air gap thickness of the lower legs and the thighs.

Figure 9 and Figure 10 shows the directional and scalar changes of the 3DGVF. As expected, the left thigh and lower leg pants parts have a similar sliding trend while the right thigh and the lower leg pants parts have a similar sling trend. The waist pants have the smallest sliding distance and sliding angles. Therefore, the motion will have limited effects on the waist pants part. The sliding of the thigh and lower leg pants parts is strong during walking. In Figure 10, it can be noticed that in the waist part through 3DGVF, the air gap thickness is larger as following order: "loose-fit" < "good-fit" < "tight-fit". This is because the dynamic air gap thickness via 3DGVF is calculated by Equation 6, which can be written as $A_p^j = \frac{1}{n}\sum_{m=1}^{n}\|pro(V_m, V_m')\| = \frac{1}{n}\sum_{m=1}^{n}\left\|V_m \times \frac{V_m \cdot V_m'}{\|V_m\| \times \|V_m'\|}\right\| = \frac{1}{n}\sum_{m=1}^{n}\|V_m \times \cos\theta\|$ $(\theta \in [0, \pi])$. For the waist parts, the L2 norms of V_{tight}, V_{good}, and V_{loose} are similar as the pants drops to a stable position. The loose-fit pants will have a larger garment sliding due to the lower pressure. So, the sliding angle follows such an order: $\theta_{loose-fit} > \theta_{good-fit} > \theta_{tight-fit}$. Because $f(\theta) = cos\,\theta$ $(\theta \in [0, \pi])$ is monotonically decreasing, the air gap thickness is in the following order: "loose-fit" < "good-fit" < "tight-fit". This observation shows that 3DGVF is efficient in describing the garment sliding. Compared to the shortest distance method, 3DGVF can be sensitive to the small changes.

5. Conclusions and future work

In this study, a novel method is proposed to determine the dynamic air gap thickness, and a new metric called 3DGVF is presented to quantitatively represent the garment sliding. Experimental results validate the proposed method. The proposed methods and 3DGVF can be used for analyzing the dynamically changing local relationships between the garment and the human body in motion. The proposed/implemented framework can be applied to the garment design industry to assist the designer to design fit clothing as well as encouraging more research on the dynamic garment-body interaction. To quantitatively understand the interaction between the garment and the human body will also make a step forward to the investigation of the correlation between air gap thickness and the thermal properties of functional fabrics [Lu et al. 2013, Frackiewicz-Kaczmarek et al. 2015] from traditional static research to dynamic research.

In summary, the main contributions of this paper are as follows:

- A novel fully automatic framework is proposed to determine the dynamic air gap thickness between the virtual garment and the human body.
- A novel method of building the 3D Garment Vector Field is presented to represent the complex interaction between the garment and the human body. To the best of literature reviews, this is the first paper to report this.

There are also some limitations. First, only the walking motion is considered in this study while the dynamic clothing fit is also influenced by motion types. The fit evaluation of individual groups such as basketball players and drivers need to be explored separately due to various motions. Therefore, to further consider the effects of motions on the dynamic clothing fit, and how to automatically design the garment for the individual group will be our future work. Second, 3DGVF depends on the geometries of the dynamic garment during the movement, which depends on the mechanical properties of the fabric such as the coefficient of friction. The implications of the mechanical properties of the fabric will be explored in the future. Third, the proposed method cannot be directly applied to the scanned data. We will improve the proposed method for the scanned data in the future. Besides, the models of muscle, soft tissue, and ligament will be introduced to enhance the realism of the human body.

Acknowledgements

This work was supported in part by the European Commission Erasmus Mundus Action 2 Programme (Ref: 2014-0861/001-001), the Engineering and Physical Sciences Research Council (EPSRC) (Ref: EP/M002632/1), and the Royal Society (Ref: IES\R2\181024, IE160609).

Reference

Bærentzen, J.A. and Aanaes, H., 2005. Signed distance computation using the angle weighted pseudonormal. IEEE Transactions on Visualization and Computer Graphics, 11(3), pp.243-253

Baran, I. and Popović, J., 2007. Automatic rigging and animation of 3d characters. ACM Transactions on Graphics (TOG), 26(3), p.72.

Botsch, M., Kobbelt, L., Pauly, M., Alliez, P. and Lévy, B., 2010. Polygon mesh processing. CRC press.

Brouet, R., Sheffer, A., Boissieux, L. and Cani, M.P., 2012. Design preserving garment transfer. ACM Transactions on Graphics, 31(4), pp.Article-No.

Eccles, L., 2011. Why most women can only dream of perfect jeans: Two-thirds can't find a pair that fit. The Daily Mail.

Frackiewicz-Kaczmarek, J., 2013. Determination of the air gap thickness and the contact area under wearing conditions (Doctoral dissertation, Université de Haute Alsace-Mulhouse).

Frackiewicz-Kaczmarek, J., Psikuta, A., Bueno, M.A. and Rossi, R.M., 2015. Effect of garment properties on air gap thickness and the contact area distribution. Textile Research Journal, 85(18), pp.1907-1918.

Han, H., Nam, Y. and Choi, K., 2010. Comparative analysis of 3D body scan measurements and manual measurements of size Korea adult females. International Journal of Industrial Ergonomics, 40(5), pp.530-540.

Han, H. and Nam, Y., 2011. Automatic body landmark identification for various body figures. International Journal of Industrial Ergonomics, 41(6), pp.592-606.

Husselmann, A.V. and Hawick, K.A., 2012, June. 3d vector-field data processing and visualisation on graphical processing units. In Proc. Int. Conf. Signal and Image Processing (SIP 2012) (pp. 92-98).

Hu, P., Komura, T., Holden, D. and Zhong, Y., 2017. Scanning and animating characters dressed in multiple-layer garments. The Visual Computer, 33(6-8), pp.961-969.

Hu, P., Li, D., Wu, G., Komura, T., Zhang, D. and Zhong, Y., 2018. Personalized 3D mannequin reconstruction based on 3D scanning. International Journal of Clothing Science and Technology.

Khoshelham, K. and Elberink, S.O., 2012. Accuracy and resolution of kinect depth data for indoor mapping applications. Sensors, 12(2), pp.1437-1454.

Kim, D.E. and LaBat, K., 2013. An exploratory study of users' evaluations of the accuracy and fidelity of a three-dimensional garment simulation. Textile Research Journal, 83(2), pp.171-184.

Kim, D.E., LaBat, K., Bye, E., Sohn, M. and Ryan, K., 2015. A study of scan garment accuracy and reliability. The Journal of The Textile Institute, 106(8), pp.853-861.

Liu, Y.J., Zhang, D.L. and Yuen, M.M.F., 2010. A survey on CAD methods in 3D garment design. Computers in Industry, 61(6), pp.576-593.

Lee, Y., Ma, J. and Choi, S., 2013. Automatic pose-independent 3D garment fitting. Computers & Graphics, 37(7), pp.911-922.

Lu, Y., Li, J., Li, X. and Song, G., 2013. The effect of air gaps in moist protective clothing on protection from heat and flame. Journal of fire sciences, 31(2), pp.99-111.

Liu, K., Kamalha, E., Wang, J. and Agrawal, T.K., 2016. Optimization design of cycling clothes' patterns based on digital clothing pressures. Fibers and Polymers, 17(9), pp.1522-1529.

Liu, K., Zeng, X., Bruniaux, P., Wang, J., Kamalha, E. and Tao, X., 2017. Fit evaluation of virtual garment try-on by learning from digital pressure data. Knowledge-Based Systems, 133, pp.174-182.
Lage, A. and Ancutiene, K., 2017. Virtual try-on technologies in the clothing industry. Part 1: investigation of distance ease between body and garment. The Journal of The Textile Institute, 108(10), pp.1787-1793.
Meng, Y., Wang, C.C. and Jin, X., 2012. Flexible shape control for automatic resizing of apparel products. Computer-Aided Design, 44(1), pp.68-76.
Mert, E., Psikuta, A., Arévalo, M., Charbonnier, C., Luible-Bär, C., Bueno, M.A. and Rossi, R.M., 2018. A validation methodology and application of 3D garment simulation software to determine the distribution of air layers in garments during walking. Measurement, 117, pp.153-164.
Nam, J.H., Branson, D.H., Ashdown, S.P., Cao, H. and Carnrite, E., 2011. Analysis of cross sectional ease values for fit analysis from 3D body scan data taken in working positions. International Journal of Human Ecology, 12(1), pp.87-99.
Psikuta, A., Frackiewicz-Kaczmarek, J., Frydrych, I. and Rossi, R., 2012. Quantitative evaluation of air gap thickness and contact area between body and garment. Textile Research Journal, 82(14), pp.1405-1413.
Psikuta, A., Frackiewicz-Kaczmarek, J., Mert, E., Bueno, M.A. and Rossi, R.M., 2015. Validation of a novel 3D scanning method for determination of the air gap in clothing. Measurement, 67, pp.61-70.
Steinbach, M., Karypis, G. and Kumar, V., 2000, August. A comparison of document clustering techniques. In KDD workshop on text mining (Vol. 400, No. 1, pp. 525-526).
Sumner, R.W. and Popović, J., 2004, August. Deformation transfer for triangle meshes. In ACM Transactions on Graphics (TOG) (Vol. 23, No. 3, pp. 399-405). ACM.
Song, H.K. and Ashdown, S.P., 2015. Investigation of the validity of 3-D virtual fitting for pants. Clothing and Textiles Research Journal, 33(4), pp.314-330.
Tong, J., Zhou, J., Liu, L., Pan, Z. and Yan, H., 2012. Scanning 3d full human bodies using kinects. IEEE transactions on visualization and computer graphics, 18(4), pp.643-650.
Thomassey, S. and Bruniaux, P., 2013. A template of ease allowance for garments based on a 3D reverse methodology. International Journal of Industrial Ergonomics, 43(5), pp.406-416.
Weyrich, T., Pauly, M., Keiser, R., Heinzle, S., Scandella, S. and Gross, M.H., 2004. Post-processing of Scanned 3D Surface Data. SPBG, 4, pp.85-94.
Welling, M., Rosen-Zvi, M. and Hinton, G.E., 2005. Exponential family harmoniums with an application to information retrieval. In Advances in neural information processing systems (pp. 1481-1488).
Wu, Y.Y., Mok, P.Y., Kwok, Y.L., Fan, J.T. and Xin, J.H., 2011. An investigation on the validity of 3D clothing simulation for garment fit evaluation.
Yu, M., Wang, Y., Wang, Y. and Li, J., 2013. Correlation between clothing air gap space and fabric mechanical properties. Journal of the Textile Institute, 104(1), pp.67-77.
Yanmei, L., Weiwei, Z., Fan, J. and Qingyun, H., 2014. Study on clothing pressure distribution of calf based on finite element method. The Journal of The Textile Institute, 105(9), pp.955-961.