SEGMENTATION AND MODELLING OF FULL HUMAN BODY SHAPE FROM 3D SCAN DATA: A SURVEY

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Abstract: The recent advances in full human body imaging technology illustrated by the 3D human body scanner (HBS), a device delivering full human body shape data, opened up large perspectives for the deployment of this technology in various fields (e.g. clothing industry, anthropology, entertainment). Yet this advance brought challenges on how to process and interpret the data delivered by the HBS in order to bridge the gap between this technology and potential applications. This paper surveys the literature on methods, for human body scan data segmentation and modelling, that attempted to overcome these challenges. It also discusses and evaluated the different approaches with respect to several requirements.

1 INTRODUCTION

The last decade has witnessed the emergence of new 3D imaging devices capable of capturing the entire shape as well as the appearance of the human body (HB). A human body scanner (HBS) is a device that generates a three-dimensional "point cloud" from the subject's frame, i.e. a constellation of 100,000 - 200,000 points generated by the body's surface. This data is saved into a simple digital format and can easily be converted to the most common computer-aided design formats. This development opens up new perspectives for human body scanners in diverse fields.

In anthropometric surveys which require collecting more than one hundred body measurements from a large population (thousands of individuals), manual measurement is time-consuming, error-prone, and very costly. In contrast, HBS technology drastically reduces the cost and duration of the surveys. Indeed, it permits rapid capture of the body shape - seconds versus minutes for a measurement by hand - and offers more consistent measurements. In addition to the speed of data collection, HBS offers reusability of data, as the scan data actually replaces the scanned subject. In effect, once extracted, the scan data can be used again and again to gather additional information, whereas a subject measured once by traditional means is no longer available for future reference.

Clothing design and human engineering are also potential beneficiaries of HBS scan technology (Paquette, 1996). The clothing industry is presently targeting custom apparel design, commonly referred to as "apparel on demand" which aims to produce clothing designed and fitted to an individual's size and proportions. This will permit better fitting garments, particularly for individuals outside the normal size range, thus reducing the cost of labour involved, and ensuring a rapid response by substantially reducing the time between measurement and delivery. HBS has a positive impact on human engineering which relies extensively on anthropometric databases (Caesar project, Online), and which is involved in custom-fitting items to human surfaces. Such items are generally used by great numbers of people and include protective equipment such as helmets, seat belts, desks, airplane and car seats.

HBS also opens up new applications in medicine and health. Gyms can use HBS data to track the effects of diet and exercise regimens. Human shape data bases will be useful for screening and survey tasks - for instance, monitoring public health problems such as obesity, and assessing child growth. HBS would be of significant interest particularly when use of other standard medical tools like X-rays are precluded for safety reasons. In fact, the relative low cost and non-invasive nature of HBS, make it a promising potential complement to current medical imaging technologies used to assist medical diagnosis, such as Computed Tomography Imagery (CTI) and Ultrasound Imagery (USI).

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Further, there appears to be a definite future for HBS in fields that involve VR applications, such as movies, television production and games (in which human-like characters appear as virtual actors, or even interact with users, usually by taking the role of an opponent). In such applications, HBS scan data can be used to provide realistic and customized models.

It is to be noted that the technology of full human shape capture is continually improving at the same time as its cost is going down. This is taking place so rapidly that novel and even unforeseen customized application areas will be realizable in the near future, considering the proliferation of personal computers and different types of communication networks. For example, a body scanner could be coupled to a PC and the captured human body shape information could then be used for any of a number of purposes, e.g. electronic commerce, ordering fitted items, or remote medical diagnosis.

Such huge potential for the exploitation of HBS raises important questions on how to process and interpret raw captured human shape data in order to extract needed information and facilitate further use of such data in various applications. In effect, the 3D point cloud data produced by HBS itself is nothing more than a collection of coordinate values, and no semantic interpretation of this data is possible. In clothing design applications and anthropological surveys, questions arise as to how to locate body landmarks used as reference points. In medical applications, how can the whole scan data set be partitioned into subsets corresponding to the principal body parts? Or, more globally, how will it be possible to effect an accurate segmentation that preserves the topological and morphological characteristics of the human body shape?

In applications involving modelling human body shape, more pertinent questions have been raised over the best way to represent the human body. In effect, while human body shape cannot be represented by simple parameterised surfaces, such as planes and quadrics, it is not a randomly-shaped free form surface either, and thus practitioners are in search of a representation that ensures maximum embodiment of human body forms while at the same time exhibiting an optimal trade-off between conciseness and expressiveness. As an example, will it in fact be possible to define a typical surface shape for the arm which can represent the full spectrum of shapes the human arm takes? And what criteria should be used in the definition of such representations?

It is hoped that this paper will shed some light on the steps taken toward answering certain of these questions. The next section offers a brief description of the technology employed in HBS. Section 3 contains a detailed overview of research done so far on human body shape analysis and modelling, while discussing and evaluating the different approaches in light of the problems and questions mentioned above. The paper concludes with some general observations and potential research orientations.

2 HUMAN BODY SCANNER TECHNOLOGY

Basically there are two categories of technology employed in HBS, laser-based technology and moiré fringing technology (Figure 1). Both are optical and involve no direct contact. In laser-based technology, which was developed by Cyberware (Cyberware, Online), a laser beam is projected from eight laser diodes onto the body, scanning it from top to bottom. The laser stripe, deformed by the body surface, is captured by different cameras around the body and recorded in a digital format. The captured data is basically the location of the laser stripe with respect to the camera reference. Afterwards a software program combines separate data from each camera, using a so-called triangulation technique, to produce a set of 3D data points representing the body surface. The duration of the scan is around 17 seconds.

Moiré fringing technology employs a moiré-based light-projection system, known also as Phase Measuring Profilometry. This system was developed by the textile and clothing technology corporation (TC^2), in Cary, North Carolina (TC2, Online). In this system, a white light source is used to project contour patterns (sinusoidal fringes) on the body surface. The contour patterns distorted by curves in the body surface are detected by a set of cameras arranged around the subject and linked to a computer. The superimposed deformed patterns thus generated interact with other patterns used as reference points. These in turn form fringes that describe the body surface contours. Subsequently the data obtained from the separate fringes are combined into a single reference yielding a cloud in which the 3D data points represent the body surface. Scan time in this technology is around two seconds.

3 LITERATURE REVIEW

Approaches dealing with HBS scan data can be classified into three themes, namely, human body landmark detection, HB scan data segmentation and human body shape modelling. However we mention that some approaches in the literature touched more than one theme. The next sections will discuss these three themes in details.

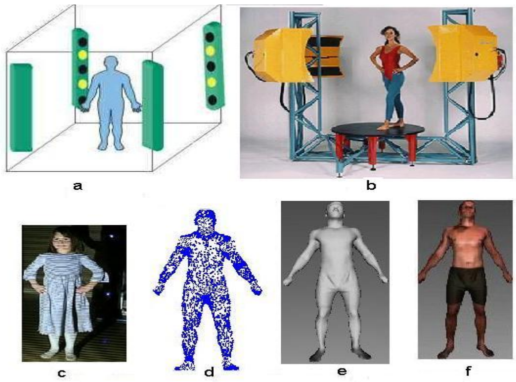

Figure 1: Basically a human body scanner is composed of an arrays of cameras and projectors arranged in a square or triangular fashion (a). The projectors produce patterns on the body surface, which are captured by the cameras and processed to generate data on the subjects shape and skin colour. The cameras and the projectors operate synchronously. Cyberware scanner (Cyberware, Online) (b) employs laser beam projectors, whereas TC^2-like scanners (TC2, Online) use Moiré fringes (c) (courtesy of Inspec: www.inspec.com). (d): Cloud of 3D Data points representing the body surface. (e): A solid model of the body surface. (f): The solid model mapped with real texture which is provided by the scanner.

3.1 Human Body Landmark Detection

Motivated by the need for automatic and accurate extraction of body measurements in apparel design applications, the very first approaches used special patterns to mark body landmarks so that they could be easily detected on images provided by the HB scanner. The work of Geisen *et al* (Geisen, 1995) is an illustrative example, in which adhesive patterns are stuck to the anatomical landmarks of the body. The positions of these patterns are detected in the image delivered by the cameras and then mapped to the 3D data points to obtain their 3D positions. However, one drawback is that the identification of the detected landmarks relies on prior knowledge of the scanned portion of the body and its relative position. Besides, using these patterns is a complication in the patient scanning assessment. Therefore, these kinds of approaches were quickly abandoned. Some authors turned towards manual solutions, e.g. Pargas *et al* (Pargas, 1997), who developed a software package in which sliced body scan data is edited and the body measurements are then extracted manually. Attempts made to automate measurement extraction were based on rough approximations of the position of the relevant body landmarks; Therefore margin of error in these measurements was significant. Using the same application, Jones *et al* (Jones, 1995) focused on the torso. A set of cross-sectional slices is manually selected in the vicinity of the key anatomical landmarks in the torso. These slices are fitted together and then interpolated to generate a NURBS approximation (a kind of CAD format). This technique ensures a viable trade-off between compactness and surface detail preservation. The approach remains particularly suited to clothing design however, and the process needs a great deal of manual intervention, although some attempts were made to automatically separate the torso and the upper part of the arms (Li, 1997).

3.2 Human Body Scan Segmentation

Automatic segmentation of the human body into its functional parts was first studied by Nurre (Nurre, 1997; Nurre, 2000). In his pioneering work, he approximated the body structure by a six-stick template representing the head, the two arms, the two legs and the torso. The goal was to segment the body into six segments corresponding to these parts. This approach combines global shape description, in particular, moment analysis and local criteria of proximity, which are derived from prior knowledge of the relative position of the body parts in standard posture (standing body with arms held at the sides). The scan data is organized into slices of data points. These horizontal slices are stacked vertically and the data points are assigned to different body parts according to the topology of the slices and their position on the body Figure (Figure 2). While this work made considerable headway towards the automatic decomposition of HB scan data, it has been criticized for imposing the requirement of limiting body poses to strict standard postures and for its lack of robustness against noise, gaps in the data, and variation of shape and posture of the HB. There have been many subsequent attempts to improve's Nurre's approach, with several efforts to enhance the localisation of key landmarks of the human body. For example, Decker et al (Dekker, 1998) improved the localisation of the key landmarks of the HB by applying differential operations on slice shape attributes, with respect to body shape modelling. They also proposed B-spline approximation of the torso (Douros,1999). Although a degree of improvement resulted from this work, this related approach could not remedy the limitations of Nurre's approach. Wang et al (Wang, 2003) proposed a new approach based on a framework employing fuzzy logic. Their segmentation technique involved local curvature analysis of the slices and operated on mesh data that must of necessity undergo several preprocessing stages. However, this again was restricted to standing postures. The overall performance of this approach remains identical to that of Nurre's. Despite the obvious improvements illustrated by these previ-

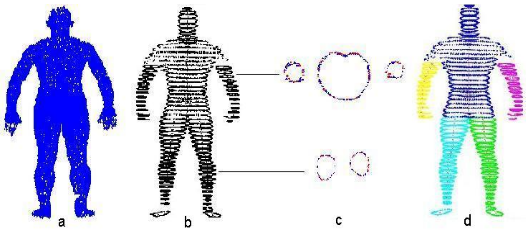

Figure 2: Segmentation of the HB data in the case of a standard standing posture (a). The scan data is sliced horizontally (b). Afterwards the slices are analyzed topologically inferring the knowledge of the human body template (c), for example, a slice having two separated closed curves must represent data points generated by the legs, a slice consisting of three closed curves must belong to the torso/arms area and a slice with two joined closed curves is assumed to correspond to the transition between the legs and the torso (at the level of groin). The output of this stage is a segmented scan data (d).

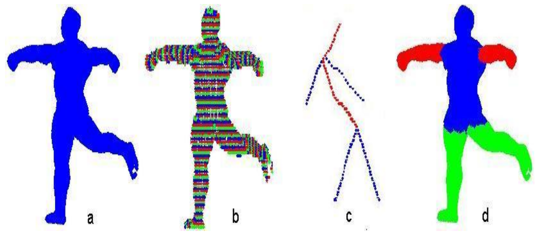

Figure 3: Segmentation of HB scan data for an arbitrary posture (a). Computation of the Level-sets (sets of data points located at the same geodesic distance with respect to a source point)(b). Construction of the Discrete-Reeb Graph (c) (a graph that encompass the human body template, and which is invariant to posture changes). The segments and the joints of the graph are then mapped to the scan data to extract the different body parts (d).

ous works, none could fully meet the requirements that one would desire in a segmentation approach. In effect, to be of practical utility, HB scan data segmentation must: 1) be robust to variation in the body surface shape stemming from biological factors such as age, genetics, etc; 2) be able to cope with changes of body posture, bearing in mind that a full recovery of the human body requires more than one posture (Brunsman, 1997); and 3) cope as well with diversity of the scan data sources as well as data deficiencies and corruption.

To solve the issue of the stability of the HBS scan data segmentation with respect to posture changes, some authors proposed the recovery of body posture from the scan data. Then once the posture is identified, the underlying information on the location of body parts can be exploited in the segmentation. Along with this benefit, posture recognition is also of interest for other applications such as human motion and gesture analysis (Lin, 1999), where the knowledge of posture intervenes in the initialisation of the tracking algorithm, and the management of three-dimensional and anthropometric databases (Paquet, 2000), where posture recognition is vital for retrieval and classification tasks (Paquet, 2001).

Werghi et al (Werghi, 2002; Werghi(1), 2005) concretised the idea of exploiting the knowledge of posture in a two-phase algorithm. The first phase involves a Bayesean classification approach, employing wavelet coefficients-based descriptors, by which the posture is identified. In the second phase a scan data slicing and analysis embodying the knowledge of posture is applied. This approach had the advantage of breaking the barrier of strict standard postures. But despite this advance, it has been abandoned because the spectrum of postures covered by this approach was limited, since as a general principle, a recognition technique, whatever its power, can only deal with a finite number of postures, and also because it could not cope effectively with scan data corruption.

In response to these challenges Xiao et al (Xiao(1), 2003; Xiao(2), 2003) proposed a robust computational topology framework that copes well against scan data corruption and diversity of the scan data source. Basically, this framework permits building a skeleton-based representation (known as the Reeb-Graph in the topological community) that encodes the human body template as well as critical points representing key body landmarks, such as the armpits and the torso. What was new in this technique was the extension of the Reeb-Graph concept to the discrete space. This new version, dubbed the Discrete Reeb-Graph, and defined on the basis of the connectivity between discrete points and curves, can operate directly on point cloud data without any special pre-processing. In the earlier version, the approach could only cope with moderate variations on standard posture, however this limitation was overcome in a subsequent version (Xiao, 2004; Werghi(2), 2005) by employing the geodesic distance (the closed distance between two points on a surface) to construct the Discrete Reeb-Graph. Being invariable to rigid transformations and isometric deformations, the geodesic distance implies a DRG construction impervious to human body movements and thus allowing a stable segmentation with respect to posture changes (Figure 3). This framework fulfils the three requirements cited above, and has in fact proven to be able to segment real-world human scans in arbitrary postures without referring to any detailed human heuristics. Further, it exhibits robustness against scan data deficiencies and diversity of scan sources. The output of this process consists of 5 sets of data points. each corresponding to a major body part, i.e. the torso (including the head), arms and legs.

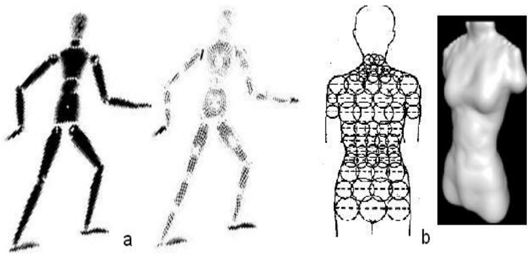

Figure 4: (a) superqadric-based model of a human body-like shape doll [24]. (b) Example of a metaball modelling, using a sphere primitive [34].

3.3 Human Body Shape Modelling

Historically the modelling of human body-like shapes (e.g. dolls, mannequins) dates from the pioneering work of Marr *et al* (Marr, 1976), who developed a hierarchical generalized-cylinder representation in which each part of the body is represented by a hierarchically decomposable set of cylinder-like primitives connected at their ends into a fleshed-out stick figure. Continuing in the same scope of application, Pentland (Pentland, 1990) went further in complexity by defining a humanoid shape by a conjunction of superquadric volumes, each associated with a body part. Motivated by shape description rather than recognition, Terzopoulos *et al* (Terzopoulos, 1991) also used superquadric primitives but, instead of a parametric representation as for Pentland, they adopted a mesh-surface model (Figure 4.a). In these two last studies, all the data is fitted to a set of generic superquadric primitives and no surface shape analysis for detecting the different body parts was involved. This problem was tackled by other authors (Borges, 1993; Dion, 1997; Ferrie, 1993; Trucco, 1991) for whom the measurement data is decomposed into sets corresponding to the different segments of the humanoid body. These sets are fitted afterward either to quadrics (Trucco, 1991), generalized cylinders (Dion, 1997) or to superquadrics (Borges, 1993; Ferrie, 1993). In the last two studies, the points of discontinuity in the range data are first detected, then dynamically grouped into contours using an energy-minimization process of deformable curves (snakes (Kass, 1988)). The contours thus obtained define the separations between areas associated with the body parts. Certain other papers attempted to address problems related to articulated structure of the human shape, more specifically registration of data corresponding to different body postures (Ashbrook, 1999).

Without a doubt, this considerable body of research has advanced the state of the art of modelling articulated objects, and the theories developed are a workable framework for approaching real human body shapes. However, tackling the case of real human body scan date appears even more challenging, firstly because the body shape is both articulated and malleable (as opposed to the rigid human-like shape treated in the above works) and secondly because the scan data is by nature non-uniformly sampled and may exhibit gaps and noise corruption. It has therefore been necessary to explore new techniques in order to formulate approaches that are better able to cope with these challenges.

Modelling of HBS data can be divided into two types: static modelling, wherein the body is not supposed to move, but local surface deformation is allowed -body scans examined in this category correspond generally to the standard static posture-; and, secondly, dynamic body modelling, wherein the aim is to model changes in shape as the body moves. The next two sections of this paper will describe these two approaches.

3.3.1 Static Body Modelling

Certain authors in this area were inspired by implicit surface models developed for human-like shapes, for instance (Shen, 1995; Matsuda,1999) used different variants of a metaballs concept, defined as iso-surface (equi-potential surface) of a field function. This concept was first introduced by Muraki (Muraki, 1991) to model anatomic surfaces from 3D range data. Basically this type of modelling consists of fitting group weighted layered metaballs to the scan data within an optimisation process. The metaball is quadric primitve, either a sphere or an ellipsoid (Figure 4.b). In this process both the weights and the number of metaballs determine the precision of the model. Implicit surfaces are however difficult to model and animate interactively because of their considerable requirements in terms of calculations and human interventions. Moreover, they cannot handle human shape details accurately, at least not without excessive computational cost. Besides, these methods fall victim to the classic optimisation issues, such as initialisation and the local minima.

Fuelled by these concerns, researchers instigated another alternative called the conformation-based approaches . The principle of such approaches consisted in coupling two models, namely, a template model that encapsulates the coarse shape, and a detail model that encompasses the local surface deformations.

Conformation-based approaches came in two versions, 2D-3D fitting (Hilton, 1999; Starck, 2001; Kakadiaris,1998) and 3D-3D fitting (Ju, 2000; Ju, 2001)(Figure 5). In the first version, 3D human body model is deformed to fit 2D body silhouettes extracted from a set of views; whereas in the second version, a generic 3D mesh model is fitted to 3D scan data via a a two-phase algorithm that consists of global and lo-

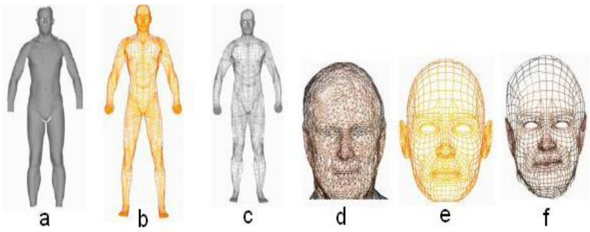

Figure 5: 3D-3D conformation technique: the 3D model (b) is fitted to the scan data (a) , the result (c) is a human body model that embeds the shape of the scanned human body. (d,e and f) the same technique applied for the case of a human head.

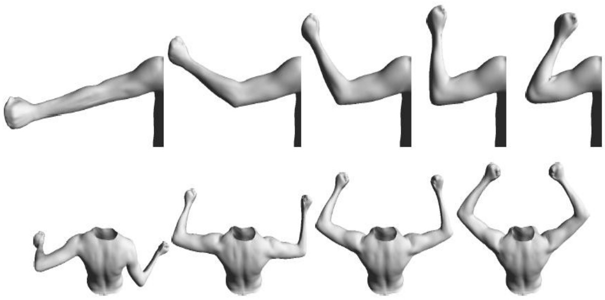

Figure 6: Examples of models generated by interpolation between two poses (Allen, 2002).

cal mapping. Global mapping involves a refined version of segmentation technique (Nurre, 1997), which is used to identify the different body segments (upper and lower arms, upper and lower legs and torso) and hence establishing correspondences between the scan data parts and the generic model parts. This method inherited however the drawback of (Nurre, 1997), namely the restriction to standard posture. Local mapping employs a closest-point correspondence technique inspired from (Ashbrook, 1998).

In the same vein, other authors (Allen,2003; Seo, 2003) developed a more elaborated approach whereby the global shape is defined explicitly by human skeleton structure. The first phase of the algorithm searches for the transformation that brings the template skeleton joints to their corresponding locations in the scan data. These are detected by either using markers on the body (Allen,2003) or manually (Seo, 2003). Local mapping is similar to that in (Ju, 2000; Ju, 2001) yet with more iterated relaxation and re-mapping to maintain the surface regularity of the generic model. The body of research work undertaken in the area of conformation-based modelling has been fruitful and has permitted achieving innovative applications such as the online garment design system described in (Cordier, 2003).

Certain other approaches have been developed recently and are worth mentioning. Wang (Wang, 2005) proposed a parametric model based on a particular continuous surface model to which is added a layer encapsulating specific details of shape. Ben Azouz et al (Ben Azzouz, 2004; Ben Azzouz, 2005) proposed a volumetric representation, wherein the 3D scan is aligned inside a volume of fixed dimension, and sampled to a set of voxels (a unit of volume). An array of signed distance between the voxels and their nearest point in the scan is then derived and used as an HB model. Principal component analysis is then applied to such representation to extract the main types of shape variation. This work has the merit of not relying on any anatomical landmarks. Victor and Paquet (Victor, 2005) used a representation that consists of an array of cords, where a cord is defined as a vector that goes from the centre of mass of the human body to the centre of mass of a given triangle modelling its surface. This obviously necessitates firstly deriving a triangular mesh model from the the HB scan data.

3.3.2 Dynamic Human Body Modelling

In fact, the topic of dynamic body modelling was studied prior to the appearance of human body scanners. The two main approaches in use today are anatomical modelling and example-based modelling. In the first, the goal is to work out as accurate a model as possible encompassing the skeleton, muscles and other interior body structures, as well as the surface of the skin, and permitting a systematic change in skin shape when the underlying structure moves. A representative works of this category are (Chadwick, 1989; Magnenat-Thalmann, 1990; Turner, 1993; Scheepers, 1997; Wilhelms, 1997; Aubel, 2001). These approaches proved to be effective in simulating body dynamics and complex collisions, however at the expense of the computational cost, as each frame requires its own simulation. Rather than looking for a complex model to synthesize body movements and deformation, the second kind of dynamic body modeling, example-based modeling, adopts a data-driven approach. The theory behind this approach involves generating models in different key poses. These poses are then correlated to various degrees of freedom, with well-defined joint angle values. New poses are generated by smoothly interpolating among these values using interpolation techniques. This type of approach seems to have been inspired by the standard key-frame techniques used in 2D animation. Authors started by using man-made human body shapes in a variety of poses, with the same underlying mesh structure to simplify the correspondence between vertices in each pose (Lewis, 2000; Sloan, 2001). When it came to real data acquired by HB scanners, these approaches met new challenges: namely, the registration between the scan data in different poses and the presence of holes and gaps inferred by self occlusions. Allen et al (Allen, 2002) addressed these problems by using markers on the subject to establish a correspondence between different poses and utilising hole-filling techniques to reconstruct complete surfaces. In the same vein, Mohr et al (Mohr, 2003) extended the skeleton model by adding fictitious joints to help simulate non-linear body shape deformation whereas local deformation is achieved via a linear regression technique that fits the vertices to the desired locations.

4 CONCLUSION

Despite being a relatively recent research area, the amount of work and research done on 3D human body analysis and modelling demonstrates the increasing interest in this topic and its wide range of potential applications.

From the above overview, it emerges that important steps have been taken towards bridging the gap between HBS technology and its various applications. Some studies have already established the successful exploitation of HBS in garment design, anthropometric applications, as well as entertainment.

A number of challenges remain to be dealt with, however. For applications involving body landmark detection, efforts undertaken to date have done a good job of extracting visible body landmarks which are apparent to the naked eye and which are at the same time reflected in the HBS. On the contrary, other landmarks are not visible, yet remain quite useful in anthropometric studies and garment design. These can only be detected by touch and compression, however, and thus are not embodied in HB scan data. One potential approach will be developing an HB Atlas that relates visible HB landmarks to invisible ones by means of geometrical formulas. For instance, shoulder points can be defined by the intersection of body contours and the lines bisecting the angle between the arm and the shoulder. Thus, invisible landmarks can be derived from visible ones once the latter are identified.

Recent work done on HB segmentation has effectively addressed serious problems and challenges such as posture variance and the deficiencies inherent in data gathered through scans. Yet much work remains to be done, especially involving postures where limbs join, for example, crossed legs, or arms touching the torso. Dealing with such cases requires discerning the contours of discontinuities between the joined parts of the body. Differential geometric techniques, topological analysis and explicit model fitting could be elements of a potential approach.

By providing real data, HBS has been of great help for researchers in improving the quality of human body models from the points of view of geometry, appearance and animation, and especially within the framework of ”modelling from examples”. Much research has already been done on applications in the clothing industry and various entertainment sectors. Despite these advances, the dream of a universal parameterised (and controllable) model of the human body embodying the full spectrum of human body shapes still appears to be quite far off. Indeed, the complexity of the human body and the diversity of factors that define its shape seem to truly plague the development of such a model. Combining anatomical modelling and example-based modelling into a single framework might be a step in the right direction.

The three main areas of research into HBS data, namely, human body modelling, body landmark detection, and HBS segmentation, are in fact quite complementary. Studies undertaken on HBS segmentation, for example, seem to have pointed the way toward solutions to important issues in the other areas in question. For instance, segmentation provides an initial labelling of the body that can be used to reduce the search space of body landmarks. In the area of dynamic human body modelling, segmentation has contributed to solving problems arising with data registration. In effect, by identifying body parts in different poses, it permits important correspondences between the related data sets, thus releasing the process from relying on manually-generated markers or set points for establishing such correspondences. It is probable that further collaboration and interaction between researchers in these three research areas will be greatly beneficial for all concerned.

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