Automatic segmentation of scanned human body using curve skeleton analysis

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Abstract. In this paper we present a method for the automatic processing of scanned human body data consisting of an algorithm for the extraction of curve skeletons of the 3D models acquired and a procedure for the automatic segmentation of skeleton branches. Models used in our experiments are obtained with a whole-body scanner based on structured light (Breuckmann bodySCAN, owned by the Faculty of Exercise and Sport Science of the University of Verona), providing triangulated meshes that are then preprocessed in order to remove holes and create clean watertight surfaces. Curve skeletons are then extracted with a novel technique based on voxel coding and active contours driven by a distance map and vector flow. The skeleton-based segmentation is based on a hierarchical search of feature points along the skeleton tree.
Our method is able to obtain on the curve skeleton a pose-independent subdivision of the main parts of the human body (trunk, head-neck region and partitioned limbs) that can be extended to the mesh surface and internal volume and can be exploited to estimate the pose and to locate more easily anthropometric features.
The curve skeleton algorithm applied allows control on the number of branches extracted and on the resolution of the volume discretization, so the procedure could be then repeated on subparts in order to refine the segmentation and build more complex hierarchical models.

Key words: Whole-body scanner, Curve skeleton, segmentation

1 Introduction

Recent advances on scanning techniques make possible to acquire high resolution models of the human body that can be extremely useful for anthropometric studies and for other applications like medical diagnosis, clothing design, computer animation and entertainment. Most of these applications could benefit of an automatic processing of the scanner data able to segment and recognize the different parts of the body and to locate reference points useful, for example, to perform anthropometric measurements. In this paper we present a processing pipeline based on the analysis of the curve skeletons of acquired models that can be used for this task.

The skeleton is extracted as a tree structure with curve segments joined at the extrema and the segmentation is performed by detecting features on the extracted branches using a priori information on the body structure. The result is a labelling of the curve skeleton and of the original mesh that can be used for several applications: feature points can be located on the basis of the functional decomposition obtained and a stick figure representing the pose of an articulated human model can be easily computed and used to control mesh animation or to fit an articulated deformable model over the data.

The paper is structured as follows: section 2 presents the state of the art of whole body scanner technology, section 3 a short literature review on scanned body data segmentation, section 4 deals with the curve skeleton extraction problem and describes the method we developed for this task. In section 5 the segmentation procedure is finally described and experimental results are presented in section 6.

2 Whole-body scanner technology

Whole-body scanners are used to build models applied in a wide range of applications such as ergonomic design, creation of sizing charts for clothing manufacture, creation of avatars for computer games and animation industry, anthropometric surveys, medical diagnosis.

Roughly speaking there are two main categories of technologies employed in whole-body scanning [16]: laser-based and Moiré-fringing-based technologies. In the former a laser stripe is projected onto the body surface. Then, the laser stripe is detected from several cameras and the set of 3D points representing the body shape are recovered by triangulation. Examples of this kind are the scanners developed by Cyberware (www.cyberware.com), Hamamatsu (www.hamamatsu.com) and Vitronic (www.vitronic.de).

In the latter, a white light source projects contour patterns, e.g. sinusoidal fringes, on the body surface. Therefore, a 3D cloud of points is estimated by observing the pattern deformations on the body surface, again from a set of cameras. Both technologies avoid direct contact with the body and fall into the category of shape from multiple views approach. The performance of different body scanners differ by resolution, accuracy, acquisition time, and organization of cameras position [16]. Examples of this kind are the scanners developed by Textile and Clothing Technology Corporation (www.dh.aist.go.jp), inSpeck (http://www.inspeck.com), and the product used for our experiments, i.e. the bodySCAN developed by Breuckmann GmbH (www.breuckmann.com). A bodySCAN typical acquisition creates a triangulated mesh with about 400.000 nodes and a resolution varying from 0.2 mm to 1.4 mm. The acquisition time ranges between 2.5 and 5.5 seconds. We found in our experiment that this time is sufficient to obtain an acceptable mesh quality (limited motion artifacts). Meshes, however, present various types of defects like holes, non manifold edges, bad shaped triangles and outliers, that should be corrected during the processing. The scanner also provides grayscale information. We do not use this information in our pipeline, but it may be extremely important to acquire, for example, markers positions useful to validate automatic measurements. Fig. 1, shows examples of acquired textured models. It is possible to see holes and inaccuracies caused by occlusions and reflective materials.

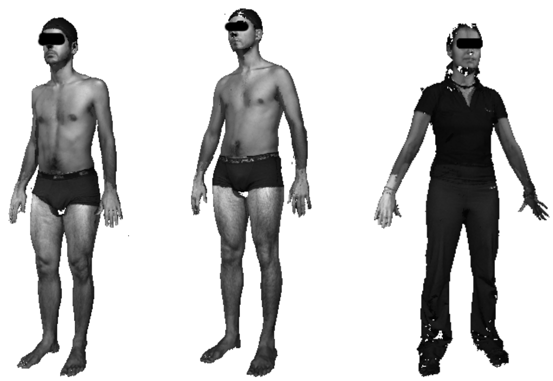

Fig. 1. Three meshes generated by the Breuckmann bodySCAN. It is possible to observe missing parts in shadowed regions and in correspondence with clothing and hair.

3 Related work

A huge literature is available on mesh segmentation. However, not so many paper deal with the reliable partitioning of a human body model into semantically consistent parts. A recent detailed review on scanned human body processing methods [16], presents and compare only few methods applied in literature to perform this task, most of them limited to standard postures, except for those developed by the authors, based on Reeb Graphs [17, 15].

Mortara et al. [7] proposed the use of a surface point classification called *plumber* in order to identify tubular region and extract body parts, performing also anthropometric measurements. Yu et al. [19] proposed a method able to find automatically joints by computing specific measurements on volume sections. The method, however, requires a previous detection of body landmarks and limbs direction.

Our approach also uses similar ideas, but starts its automatic processing by first extracting and segmenting the curve skeleton of the model. In this way it is possible to process the curve skeleton branches corresponding, for example to the limbs and to perform local measurements useful to locate landmarks or joints without slicing in pre-defined directions the surface. Recently, we discovered that this segmentation approach is close to that proposed by Reniers and Telea [2], who implemented a generic method for skeleton-based mesh segmentation. Our method differs from theirs because it exploits a priori information on human body structure in order to simplify the curve skeleton and to recognize its parts and for the use a feature point search on skeleton branches in order to define cut points for the skeleton.

4 Curve skeleton extraction

The literature on curve skeleton extraction is also huge, even if surprisingly recent. Despite its apparent simplicity, in fact, the extraction of a 1D connected curve skeleton from volume data presents several problems, and even the definition of a curve skeleton is not easy, as pointed out by Cornea et al. [10].
The first methods successfully applied were those based on topological thinning [11], i.e. the iterative removal of external voxels preserving the topology or on the computation of distance maps from the border as in the voxel coding method [18]. They gave useful results, especially in the medical field, where the estimation of a centerline path in vessels is fundamental their characterization and measurement. These techniques, however, usually required interaction to place seed points or extremal points of the skeleton to be preserved. Furthermore results obtained were usually not reliable for non tubular objects.

A variety of approaches has then been proposed to overcome these problems. Telea and van Wijk [1] used the intersection of 2d skeletons for a fast 3D skeleton extraction, Cornea et al. [9] used a fast marching method, Sharf et al. [13] obtained the skeleton "on the fly" while reconstructing the mesh with a surface growth. Shapira et al. [12] used a function defined on the surface (Shape Diameter Function) in order to find approximate skeletal points then fitted into curves. Dey and Sun [4] removed ambiguities in curve-skeleton definition by considering it as the subset of the medial axis where a function called Medial Geodesic Function can be defined and is singular. A similar approach, but defined on voxelized volumes has been used by Reniers et al. [3]. Drawbacks of these approaches are the complexity of the discretization steps and the computational weight of the geodesic path evaluation.
For our mesh processing pipeline we adopted for the curve skeleton extraction a novel method inspired by that applied in [5] to vascular reconstruction and based on voxel coding and active contours. This method is good for our task because it allows a fast extraction of a connected structure, thin and smooth, well centered in tubular regions and with no closed loops by construction. Furthermore, it is possible to limit a priori the number of branches to extract neglecting shorter ones and to define the resolution of the curve skeleton, an useful feature for the hierarchical processing of parts and subparts of the human body we plan to develop.

Let us describe the method in more detail. The process starts with a raw extraction of a tree structure with a voxel coding method, like in [18]. The mesh is discretized in a 3D grid of given dimension (the resolution can be adapted to the level of detail, for human body we start with 5 mm of voxel size). Border voxels are then extracted and a distance map computing the distance of internal voxels from the border (DFB map) is generated. The classical voxel coding method

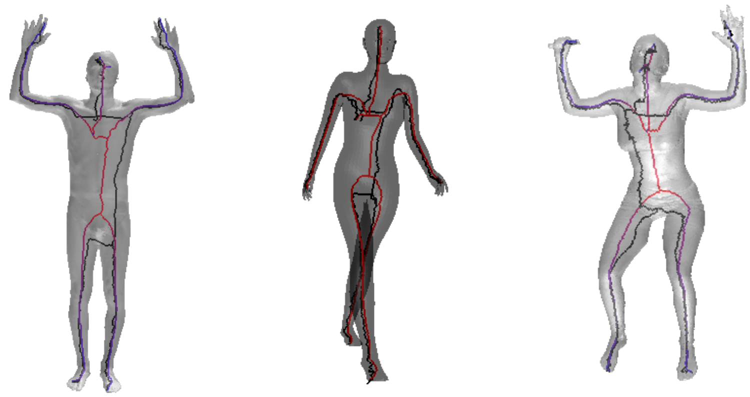

Fig. 2. Examples of curve skeletons extracted on human body models, meshes are represented as transparent surfaces, non-centered paths are represented in black, centered and cleaned trees are represented in red. Examples are chosen in order to underline that the characterization obtained is almost pose-independent.

by Zhou and Toga then extracts iteratively branches by giving a seed point, computing the “distance from seeds” (DFS) map and then using it to compute the shortest voxel path joining the farthest point to the seed. The path is then centered by replacing each voxel of the chain with the voxel obtained by first finding the cluster of the connected voxels with the same distance from the seed, and then taking the voxel with the highest distance from border. It has been shown in [5] that this centering procedure can give very bad results in case of non tubular shapes because clusters can be large and the curve may result not continuous. We therefore do not use this method to center the branches (we just perform optionally this step as pre processing), but exploit an active contour approach instead.

Our method consists of first creating a tree structure joining several branches. After the extraction of the first branch as the shortest path joining a seed placed near the mesh border and the farthest voxel of the volume, and its rough centering, a recursive shortest path extraction is done in the same way updating the distance from seed at each iteration as the distance from the previously extracted skeleton point.

The procedure can be iterated until branches are shorter than a threshold or a sufficient number if branches has been found (this is our case). The skeleton, consisting of nodes with floating point coordinates and links is then centered moving iteratively the nodes according to external forces driving the contour and other constraints. In detail:

– two image based forces are applied to the skeleton points: the first is directed as the gradient of the interpolated DFB map, the other is generated with a fast propagation of the internal normal vector at the boundaries. This last force is used not to have ambiguous stationary points in the medial surface.

- The internal forces are generated by a mass-spring model, with masses at the node positions and zero length springs connecting them.
- During the curve evolution, terminal nodes are kept fixed, links are preserved and new nodes are inserted when the distance between neighbors is higher than a threshold and removed when it is lower than another threshold.
- If two curve segments are partially superimposed, the duplicated part is removed and new links created.
- The iterative procedure is stopped when the global displacement is lower than a threshold.

In our implementation, after the mesh discretization, the seed point for the extraction of the first branch is taken as the surface voxel with the highest z coordinate. Rules chosen for the curve evolution makes, in any case, the results substantially independent on this choice. Weights for the snake forces have been set by trial and error.
Results obtained are satisfactory: the algorithm is fast and robust and curve skeletons obtained are well centered (see Fig. 2). The active contour approach presents the big advantage of keeping the curves smooth, avoiding the discontinuity problems of classical methods based on local geometrical properties and clustering.

5 Curve-skeleton based segmentation

The curve skeleton is then subdivided in segments, i.e. chains with no links except at the extremal nodes. Segments can be divided in leaves, i.e. chains with links at only one of the extremal nodes, and internal segments, i.e. chains with links at two extremal nodes (Figure 3 A).
The processing pipeline consists then in two steps: first candidate skeleton branches containing the main body structure are isolated, then branches are processed in order to find feature points used to segment them correctly. In order to find the human body components we process the skeleton as follows: first we remove the shortest leaves as follows:
-leaves are put in a list ordered by length
-the shortest leaf is removed and if its endpoint is linked to two segments, these segments are merged. The procedure is ended when the list includes only 5 leaves. Each leaf should include the complete skeleton of one structure among the limbs and to the head/neck (Fig 3 B). Finally, a simple decision tree based on length and distance functions of the leaves is able to label them according to the structure included (arm, leg, head).

5.1 Feature extraction on the curve-skeleton

Leaves, i.e. candidate skeleton branches that should include limbs and head/neck, are then processed in order to find the optimal position of feature points. These points are the approximate location of limbs an neck attachments to the trunk,

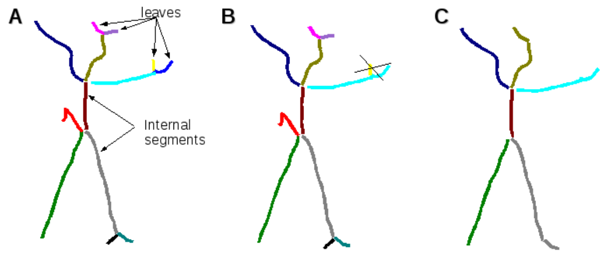

Fig. 3. The procedure used to purge the skeleton tree preserving the five main leaves including the parts to be segmented. A: original skeleton. B Shortest leaf is removed and the connected branches merged. C: The procedure is stopped with five leaves left.

and the approximate position of knee and elbow joints, wrist and ankle joints. In order to approximately locate these points on the curve skeleton we considered the behavior of four selected scalar values along the leaves extracted: the local interpolated distance from border, estimates of local average diameter and eccentricity of the section perpendicular to the curve, and an estimate of the local curvature.

Fig. 4 shows examples of the typical behavior of the first three values on leaves including arm, leg and head/neck. Curvature is not reported being pose-dependent, so its behavior is not characteristic. It is possible to see that the interpolated DFB is a slow-varying measure and can capture the general trend of the diameter of the mesh around the evaluated branch. Mean diameter is more sensitive to the local structure (and to noise) and can be used used to capture subtle features. Particularly interesting is the eccentricity estimate, well-suitable for joint feature extraction as also reported in [19].

Our segmentation method is hierarchical: first the attachments of the limb or of the neck to the trunk are found starting from the middle of the branches and moving towards the trunk until the eccentricity value presents a big step edge.Currently we place the starting point of limbs in the location where the value becomes stationary. Wrists and ankles are then searched by finding in the lower part of the branches the local minimum of the section diameter following the large local maximum corresponding to forearm/calf muscles. Feature points are then located in the subsequent edge in the section diameter (location of maximum of the diameter increase). More difficult is to locate accurately elbows and knee. They are currently identified by the maximum in the curvature if well characterized, otherwise they are located at the extrema of the deviation of the diameter and of the distance value from the linear growth. If the feature point is not clearly visible in this way we locate first a different feature point, i.e. the location where the forearm/calf muscles starts, characterized by a minimum in the local diameter, and the position is then refined by shifting the detected point on the path of a distance proportional to the average distance on the two feature points on test cases and to the leg length. The position of the detected points is then finally refined with an iterative procedure adding the constraints of symmetry between left-right legs and arms. Finally, we locate the feature point used to separate the head from the trunk by extracting from the eccentricity plot not only the edge corresponding to the beginning of the neck but also the one corresponding to the neck attachment to the head and put the feature point in the middle of the neck.

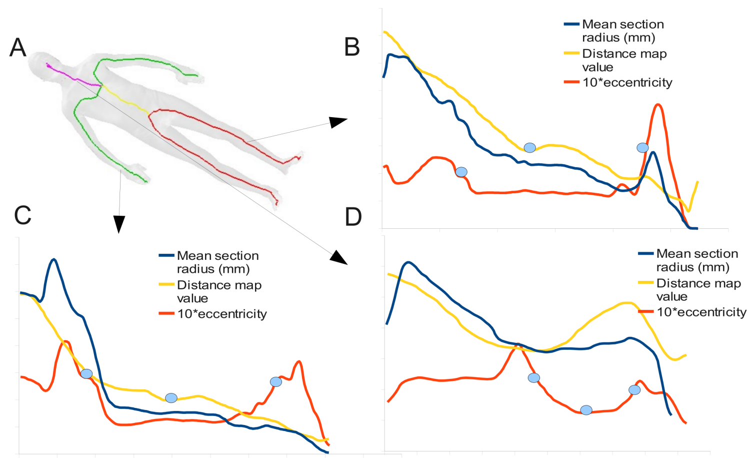

Fig. 4. Example of the behavior of selected scalar measures computed on curve skeleton points on the different skeleton leaves. A: The original mesh, with the curve skeleton extracted. Leaves are represented in different colors. B,C,D: Plots of DFB, average section radius and eccentricity along the leaf including an arm, a leg and head and neck. Dots indicate the approximate extracted position of the feature points.

When a reasonable number of scans will be available, we plan to build statistical models of the behavior of the computed values near the interested points and to locate them fitting the models to the data.

5.2 Mesh segmentation

Mesh points can be easily labelled according to the skeleton partitioning. We label the discretized space computing a distance map of the volume voxels from the final skeleton. Triangles of the mesh are then labelled according to the label of the voxel including its center. Being the space partitioning not depending on the mesh triangulation, the mesh labelling can be performed also on the processed mesh as well as on the original one.

5.3 Pose estimation

Human pose estimation can be achieved by finding the best fit an articulated stick figure over the acquired data. This is extremely simple in our case, having a rough estimation of the positions of the nodes of the articulated model from the skeleton analysis. It is therefore immediate to calculate a rough pose estimate by connecting the detected feature points with segments. Methods based on hierarchical articulated model fitting (like, for example, the method described in [8]) could be applied as well.

6 Experimental results

We tested our pipeline on 8 meshes acquired with the Breuckmann scanner. A pre-processing is performed by generating a closed volume from the original incomplete mesh. This step is currently done using Polymender, a fully automated software for mesh repairing based on the procedures described in [6]. Algorithm and package have been chosen due to their simplicity and robustness, it must however considered that the reconstruction is obviously not accurate where the original mesh presents large holes due to occlusions (i.e. at limb joints, under the shoulders and between the legs). In these regions, the repaired meshes do not follow the natural curvature of the skin as would be expected. However, being our processing pipeline based on the curve skeleton and not on surface features, the effects of this inaccuracy are limited.

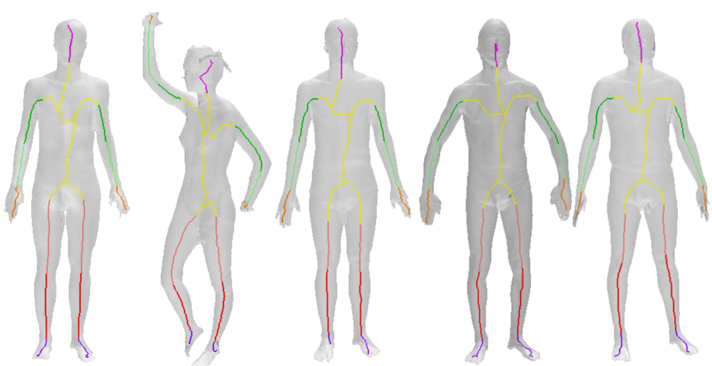

Fig. 5. Examples of curve skeleton partitioning on data obtained from the Breuckmann body-scanner

On all the acquired mesh the curve skeletons automatically extracted appear correctly located, smooth and well centered in the tubular parts.

Fig. 5 shows example partitioned curve skeletons extracted on the Breuckmann scanner models. The labelling of the body parts is correct for all the datasets tested. The position of the feature points is, of course, rough and also more influenced by holes and inaccuracies of the original meshes. Only in a few cases, however, points appears a bit shifted from the expected position. Despite

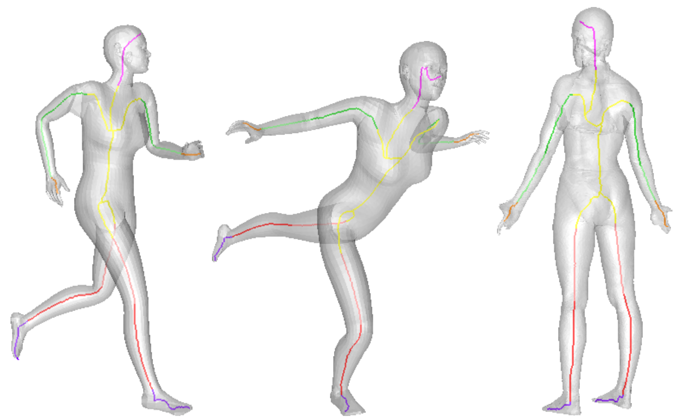

Fig. 6. Results obtained on human body meshes from the aim@shape database.

these limits in the accuracy, the body partitioning obtained can be extremely useful for several practical tasks, like fitting hierarchical models or stick figures to the data or reducing the search space for anatomical features on the mesh surface.

In order to evaluate the robustness of the curve-skeleton extraction and labeling methods against pose variations, we also tested the body partitioning on five watertight meshes representing human body in different poses, available from the Aim@Shape Watertight dataset[14]. Results obtained (see Fig. 6) show that the recognition of the body parts and the location of feature points is possible independently on the pose (but obviously requiring the sphere-like topology).

The left part of Fig. 7 shows examples of mesh labelling induced by the skeleton segmentation. The accuracy of the surface boundaries is obviously limited, we plan, however, to refine the segmentation using surface information. The right part of the figure shows an example of stick figure obtained from the processed skeletons superimposed to the original meshes. Results may be improved by considering that the feature point at the beginning of the limbs are not exactly corresponding to the articulation, and should be slightly displaced. The articulated models obtained seem, however, suitable for articulated model fitting and computer animation.

7 Conclusions

We presented a pipeline for the fully automated segmentation of volumetric data acquired with a whole body scanner. This pipeline is intended as a first step on order to have an automatic extraction of useful information for anthropometric studies. The original contribution proposed in this paper consists mainly of
-A novel algorithm for curve-skeleton extraction, based on voxel coding and active contours driven by a distance map and vector flow.

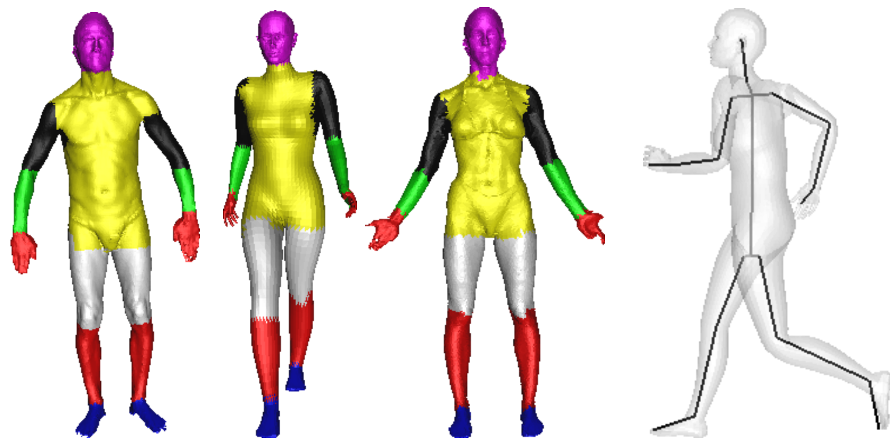

Fig. 7. Left: examples of mesh labelling derived from the skeleton partitioning. Right: A stick figure obtained from the feature points located with the described technique.

-A curve-skeleton based body segmentation algorithm, based on a priori information and the search of feature points on scalar functions computed on skeleton points.
An interesting aspect of the procedure proposed is that it can be performed iteratively on the segmented parts, increasing the resolution of the curve skeleton extraction in order to have more detailed models after the first rough classification of the parts. We plan to segment automatically in this way hands and feet. Results obtained are promising even if preliminary and a lot of further work is planned to carry on the whole body scanner segmentation pipeline. We plan, in fact, to characterize better the position of the characteristic points on the curve-skeleton by building statistical models of the skeleton features and registering them with the acquired data for a precise localization. We should also improve the mesh segmentation derived by the skeleton labeling by making the boundaries computed on the surface attracted by curvature edges. To perform anthropometric measurements, we plan to develop algorithms for the detection of meaningful features on the surface, exploiting the a priori information acquired with the mesh partitioning to simplify the problem narrowing the search space. Finally, we want to improve and exploit the pose estimation obtained from the curve skeleton in order to fit generic human body models to the scanner data. This procedure could greatly enhance the quality of the human models automatically reconstructed from the scanner data, providing directly realistic watertight meshes also when the acquired data are incomplete or not reliable.

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