

Image Warping of Three-Dimensional Body Scan Data

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ABSTRACT

This paper details the application of three-dimensional image warping techniques to full body scan data. Borrowed from the toolbox of geometric morphometrics—methods commonly used to quantify the size and shape of anatomical objects in biological research—image unwarping transforms a given image such that relevant landmark positions of the starting image coincide with their positions in the consensus or target configuration. This study demonstrates the process of transforming static scan data to any posture, position, or homology for which landmark data is available, enabling detailed human models to be re-postured and examined in design environments widely varied from the one in which they were scanned.

INTRODUCTION

In his 1917 work, *On Growth and Form*, the biomathematician D'Arcy Thompson outlined an elegant approach for comparing shape differences between two or more objects (specimens, species, etc.) through the use of “transformation grids” [1]. Thompson proposed describing the form of one organism as distortions in the shape of a reference organism. He hypothesized that by placing a Cartesian coordinate grid over the image of the reference organism and then distorting this image (including the grid) until the image of the reference matched that of the target, it would be possible to show differences in the shapes of the two organisms as deformations of the fitted grid.

More recently, a method of generating transformation grids that exactly map the configuration of landmarks for one organism to that of another has been implemented by Bookstein through the use of thin plate splines [2]. The thin plate spline technique is a method for interpolating surfaces over irregularly spaced data by

expressing the dependence of the physical bending energy of a thin metal plate on point constraints. In the field of geometric morphometrics, the thin plate spline has been used to graphically display the deformations required to interpolate between landmark configurations representing significant feature points of different organisms.

The thin plate spline is particularly useful in these cases, as it exactly maps each two or three-dimensional landmark in a reference specimen to the corresponding landmark in a target specimen while minimizing the net “bending energy” required for the interpolation. The spline mapping describes the landmark transformation, but can be used to transform grid lines, outline contours, and any other image features which represent the organism. Of particular interest in the field of morphometrics and comparative biology is the use of thin plate splines to “unwarp” an image. After calculating a thin plate spline mapping based on landmark interpolation from a reference to a target, the grayscale values from the target image are transferred pixel by pixel to that of the reference, resulting in the generation of an image for the reference specimen. The average image is then used to visually represent the shape of any specimen in the data space. Bookstein [3] called this approach *image unwarping* (see also [4]).

This paper details an initial exploration of the application of thin plate spline and image warping algorithms to three dimensional landmark and full body scan data. (The distinction between image warping and image unwarping will be explained in a subsequent section.) While the use of the thin plate spline to analyze three-dimensional data is not uncommon, the inclusion of 3D image warping is relatively new. This paper will explore the methods required to generate full body scans for body positions or landmark homology that is independent of the original scan position.

$$\iint_{R^2} \left(\left(\frac{\partial z}{\partial x} \right)^2 + 2 \left(\frac{\partial z}{\partial x \partial y} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right) dx dy. \quad (3)$$

Two tests of the thin plate spline and warping algorithms are explored: the transformation of a full-body scan from a standing posture to a seated posture using landmark data for the same subject in each posture as the reference and target data sets, and the warping of a standing posture scan for a given subject by the homology of a second individual. The applications of these methods are numerous, and extend into any field for which digital human models aid in design, visualization, or analysis. When applied to full-body scan data, these techniques can unwarped the xyz vertex and color data from one scanned position to other positions for which landmark data is known. The end result is an image—a full color, three-dimensional surface scan—positioned in the new, target location.

CALCULATING THE THIN PLATE SPLINE

The thin plate spline method describes the deformation of a thin metal sheet on point constraints in such a way that the physical bending energy of the plate is minimized. The application of these methods to the generation of spline data was pioneered by Duchon [5] and formalized by Meinguet [6,7]. The mathematical methods that follow were adapted by Bookstein [2,3] to the problem of two-dimensional interpolation.

The thin plate spline algorithm specifies the mapping of points for a reference image or specimen to corresponding points on a target image or specimen. For interpolations in two dimensions, these data can be visualized as lying just above or below the plane of a thin metal plate. In a physical setting, displacement of the plate or spline surface occurs in a direction orthogonal to the plate. If the plate is defined as lying in the x, y plane, then these displacements, $z(x, y)$, describe the surface

$$z(x, y) = -U(r) = -r^2 \log r^2 \quad (1)$$

where r is the distance in p dimensions (i.e., $\sqrt{x^2 + y^2}$ for 2D) from the Cartesian origin. (The three-dimensional solution will be addressed later in this section.) When this model is applied to the problem of coordinate interpolation (i.e. image or scan warping), the lifting or warping of the plate in the z direction is interpreted as displacement of the x or y coordinates within the plate. Thus, for two-dimensional interpolations, thin plate spline calculations define a map $R^2 \rightarrow R^2$ with the following function

$$f(x, y) \rightarrow f(x', y') = (x, y + z(x, y)) \quad (2)$$

in which $z(x, y)$ is the vertical displacement of the metal sheet and minimizes the integral bending norm

The function $f(x, y)$ exactly maps all landmark points in the reference to corresponding points in the target. In matrix form, (x, y) is mapped to (x', y') as

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \mathbf{A} \begin{bmatrix} 1 & x & y \end{bmatrix} + \sum_{i=1}^n w_i U(r), \quad (4)$$

where n is the number of common landmark points to interpolate between the target and reference specimens. $U(r)$ is calculated as the distance between landmark i and the current (x, y) point in the reference image. The matrix \mathbf{A} contains parameters for the affine or linear transformation of the landmarks—including translation, rotation, scale, and shear—and is multiplied by a matrix containing the full set of image or scan data points for the reference specimen augmented with a column of 1s. The matrix w includes parameters for the non-affine deformation. \mathbf{A} and w are based upon the relationships between the reference and target landmark points and are determined in the following way:

Define \mathbf{P} as an $n \times (p+1)$ matrix of reference landmark points preceded by a column of 1s in which n is the number of p -dimensional points.

$$\mathbf{P} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & \dots & \dots \\ 1 & x_n & y_n \end{bmatrix} \quad (5)$$

\mathbf{K} is defined as an $n \times n$ matrix of the $U(r)$ functions of the distances between landmarks in the reference

$$\mathbf{K} = \begin{bmatrix} 0 & U(r_{12}) & \dots & U(r_{1n}) \\ U(r_{21}) & 0 & \dots & U(r_{2n}) \\ \dots & \dots & \dots & \dots \\ U(r_{n1}) & U(r_{n2}) & \dots & 0 \end{bmatrix} \quad (6)$$

and

$$L = \left[\begin{array}{c|c} \mathbf{K} & \mathbf{P} \\ \hline \mathbf{P}^T & \mathbf{O} \end{array} \right] \quad (7)$$

where \mathbf{O} is a $p \times p$ matrix of zeros. \mathbf{A} and w are found from the inverse of L by the equation

$$L^{-1}Y = (W \mid a_1 \ a_x \ a_y)^T \quad (8)$$

in which

$$Y = (V \mid 0 \ 0 \ 0)^T \quad (9)$$

such that Y is an $(n + p + 1) \times p$ matrix of the landmarks of the target specimen V , augmented by $p + 1$ rows of p 0s.

Modifications to the thin plate spline algorithm in order to change from a two-dimensional to a three-dimensional analysis ($p = 3$) are minimal, and include solving $U(r)$ using three-dimensional Cartesian distances, and calculating $U(r) = |r|$ rather than $U(r) = r^2 \log r^2$. The thin plate spline mapping function (4) becomes

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = A \begin{bmatrix} 1 & x & y & z \end{bmatrix} + \sum_{i=1}^n w_i U(r) \quad (10)$$

in which the input (x, y, z) are the set of points for the full reference image or three-dimensional scan. There should also be slight modifications to P (now an $n \times 4$ matrix), L , and the equations for Y :

$$L^{-1}Y = (W \mid a_1 \ a_x \ a_y \ a_z)^T \quad (11)$$

$$Y = (V \mid 0 \ 0 \ 0 \ 0)^T \quad (12)$$

WARPING VS UNWARPING OF SCAN DATA

In standard applications of image unwarping, the reference organism is an estimated shape (often the overall average) and does not physically exist. To produce an estimated, unwrapped image, the image of each specimen in the analysis is first transformed to the configuration of the reference specimen (using the thin plate spline) such that the image's landmarks align with those of the reference shape. The pixel values of these images are then averaged to produce an estimate image for the reference.

In order to use image unwarping techniques to generate the three-dimensional scan data for a subject in a seated posture from data of the subject in a standing posture, it would be necessary to perform a thin plate spline analysis using the seated configuration of landmarks as the reference and the standing configuration as the target. After the thin plate spline analysis, the spline mapping would be used to transform a three-dimensional grid of dense, equally spaced points describing the volume of the model of the reference configuration. The transformed grid data is then unwrapped by transferring each vertex point within the target model's grid to the corresponding grid location in the reference. The final result is the generation of a model of the target in the reference posture.

While this technique would produce the desired results, the same effect may be achieved in this application by simply warping the reference to the target configuration directly. For the transformation of an individual body scan, the reference is a subject, not a sample, thus an image for the reference already exists and can be warped directly to the target configuration. In addition, the three-dimensional image description is defined as a collection of polygons specified by sets of vertices. The vertex-polygon relationships remain unchanged by warping, thus the vertices themselves may be warped and the model of the target posture rendered with the new vertex locations. The space within and around the model need not be described for image warping of an individual model.

Using warping instead of unwarping methods dramatically reduces computation time, as unwarping of the 3D data would require applying thin plate spline mappings to an extremely large number of three dimensional points in order to designate a grid that would produce adequate resolution of the finished scan. The extents of the standing posture scan for an average male subject are 1.2 meters by 1.23 meters by 1.69 meters. To place a vertex point every centimeter in this space would require a 120x123x169 grid including 2,494,440 point calculations, many of which represent empty space around and within the model. For resolution of a millimeter, this value increases by a factor of 100.

APPLICATION OF THE THIN PLATE SPLINE: STANDING TO SEATED WARPING

The initial test of the three-dimensional thin plate spline algorithm was to warp a full-body scan of a male subject from a standing, reference posture to a seated, target posture. The test data was obtained from the CAESAR (Civilian American and European Surface Anthropometry Resource) study, a 3D surface anthropometry survey of body measurements of people between the ages of 18-65 across the United States, Italy, and the Netherlands[8]. In the CAESAR project, complete 3D scans of each subject in a standing, seated, and seated "coverage" posture were obtained through the use of a 3D laser scanner. The scanners captured both range and color data, allowing for the extraction of three-dimensional locations for 73 anthropometric landmark points which had been indicated on the subject by the placement of reflective markers.

Subject 1073 (Figure 1) was selected for this analysis due to the relatively low number of missing landmarks in his seated scan: 66 of the 73 measured landmarks were present. Three-dimensional landmark points in both postures were available from the CAESAR survey, as were both full-body scans. The standing posture scan was selected as the reference image as it provided maximum coverage and visibility of the body, including distinct separation between the arms and the trunk. For this particular analysis, the seated scan was used only as a means of comparing the results of the image warping to the seated position.

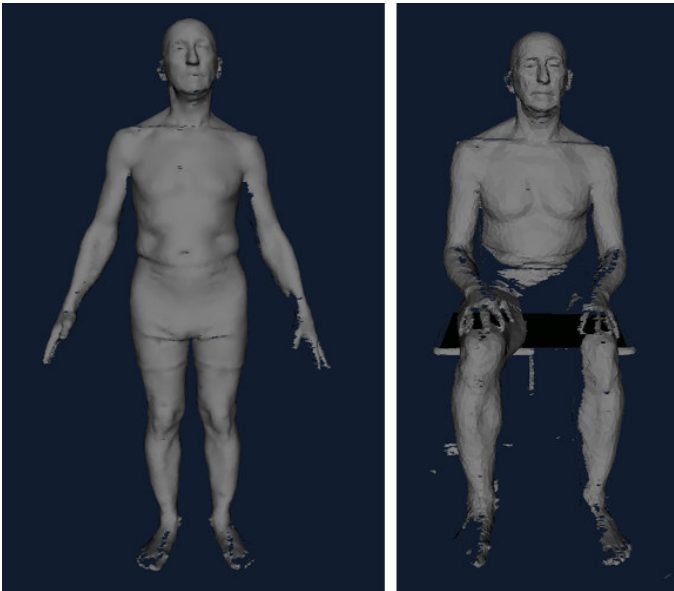


Figure 1: Original CAESAR standing (left) and seated (right) full-body scans.

In order to minimize variation due to differences in position, landmark data sets aligned by mean-centering. Rotational alignment was standardized during the scanning process itself.

INITIAL RESULTS

The results of this analysis appear in Figure 2. As the thin-plate spline functions transform only vertex position, it was possible to apply the original polygonal relationships to the new vertex locations and thus generate a polygonal model that was suitable for visualizing the results.

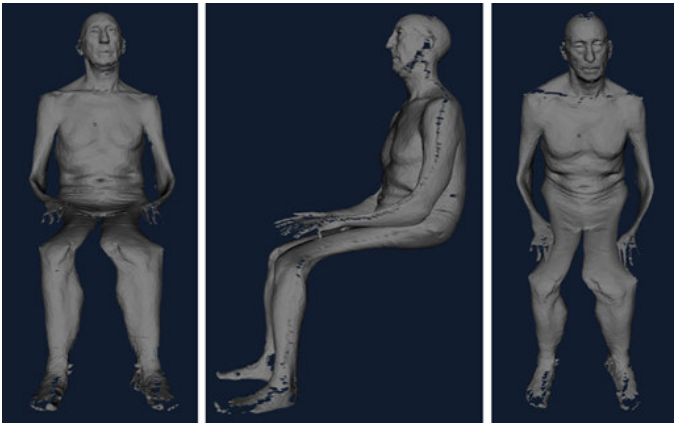


Figure 2: Front, right side, and top images of complete reference scan warped to target position using 66 landmark points.

This mapping reproduces the basic structure of the subject and provides correct posturing, but fails to maintain the subject's true form. The arms are deflated, the thighs squashed and malformed. Local displacements seem to have overlapped and affected one another, with the repositioning of the arms resulting in a flattening of the forearms and a deformation of the space above the thighs. It is important to note that while

these results do not produce an aesthetic digital model, the thin plate spline method has produced an exact mapping of all landmark interpolants. The extents of the subject as described in the reference and target data set are accurately described by the final warped scan. It is apparent, however, that this analysis does not include enough landmarks to accurately describe the entire mapping from reference to target. In this example, the complexity of the deformation is not adequately expressed by only 66 interpolants.

SEGMENTATION OF THE SCAN

In their efforts to morph the human face, Blanz and Vetter [9] found that the effectiveness of a warping transformation could be increased by dividing the surface scan into separate subregions that could be warped independently. Such segmentation is equivalent to subdividing the entire shape space for a single subject into independent subspaces for each scan segment. These methods were applied to the full body scan data in an effort to improve the warping transformation. Segmentation was based on the results of the first seated transformation, and four regions were selected to minimize subspace overlap during warping: a left arm and a right arm segment; an upper-body region including the chest, head and neck; and a lower body region composed of the torso, buttocks, and left and right legs. Generation of a complete 3D body scan was achieved by warping each segment separately using reference and target landmark sets which overlap across segments and then combining the final warped models.

In order to further improve apparent goodness-of-fit, additional landmarks were selected from the standing and seated scans. These landmarks, though more arbitrary than the original 66, serve to augment the analysis and improve the localized deformations in areas where the mapping was not well defined [3]. These augmented landmarks included: top of the pants on the subject's left, right, and posterior sides; additional left and right buttock points; posterior thigh at the clothing line; anterior thigh at the clothing line; lateral thigh at the clothing line; top of the patella for the left and right leg. A total of 15 landmarks were used for each arm, 31 for the upper-body region, and 33 for the lower-body region. It should be noted that the use of these additional landmarks in the warping of the full body scan improved the results in a few, local areas, but that the effect of the arm and thigh subspace overlap was still quite dramatic.

SEGMENTATION RESULTS

The results of the segmented thin plate spline analysis appear in Figure 3. From these images, it is apparent that segmentation of the body scan data and augmentation of the set of landmark interpolants has improved the overall mapping. Form has been more accurately preserved, and deformations are indeed more localized. The stomach has compressed down and bulged outward to fit the new posturing, and the thighs have flattened to correspond with deformation against a

stool. Some deformation is apparent in the calves due to the lack of landmark descriptors present in that area, but the overall shape and musculature is still present. The arms have flattened around the elbow joint, owing to the lack of landmark data describing the inside of the arm. In spite of these deformations, the upper arms retain musculature present in the original reference scan.

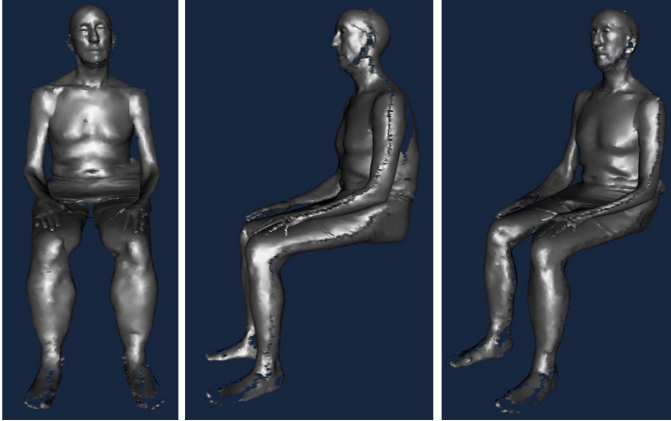


Figure 3: Front, side, and perspective views of standing reference scan warped to target seated position using segmentation method.

APPLICATION OF THE THIN PLATE SPLINE: MAPPING BETWEEN SUBJECTS

The next analysis explores the use of the thin plate spline method to warp the scan of one individual by the homology of another, producing an estimated image for the target subject. For this test, subject 1122 was selected as the target as his body shape and size were considerably different from those of reference subject 1073. The between-subject mapping was performed on the standing posture data for both subjects in order to focus on homology changes rather than deformations due to reposituring. As there would be no extreme repositioning of the subject, segmentation of the scan data was not deemed necessary.

The results of the homology mapping appear in Figure 4. In these images, the landmark markers are visible as bright spots on each subject's body. Based on primarily the mapping of these interpolants (two supplemental landmark points were used to fill in missing values), subject 1073 was repositioned and enlarged to match subject 1122's landmark configuration. Visible deformations include a shortening and widening of the facial features, shortening of the arms and repositioning of the hands, enlarging of the chest and torso area, and broadening of the shoulders.

Figure 5 includes a side view of the same scans. In these images, the expansion of the torso and reposituring of the head relative to the shoulders can be more clearly seen. Some of the differences in overall stomach and buttock shape can be attributed to lack of landmark descriptors in this area.

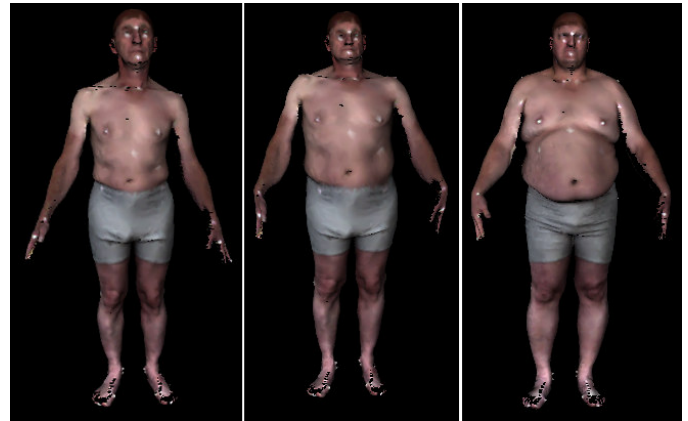


Figure 4: Subject 1073 (left), subject 1122 (right), and the results of a thin plate spline analysis using 1073 as the reference and 1122 as the target (center).

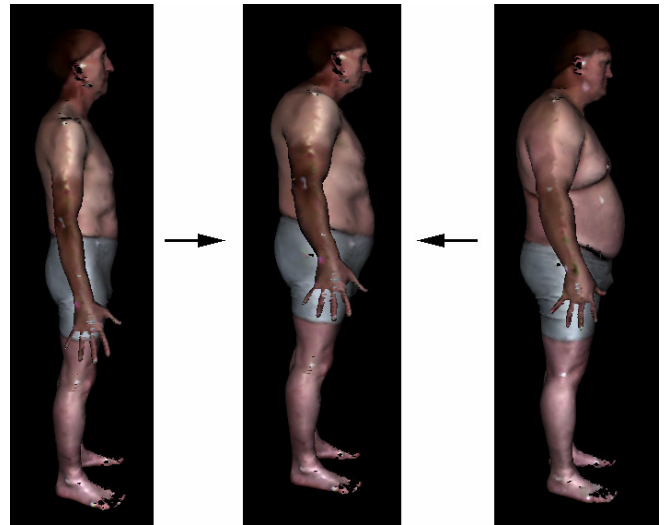


Figure 5: Side views of subject 1073 (left), subject 1122 (right), and the results of a thin plate spline analysis using 1073 as the reference and 1122 as the target (center).

CONCLUSIONS

The thin plate spline algorithm is an accurate method of exactly mapping landmarks in a reference specimen to corresponding landmarks in a target. For human figure data, the set of reference landmarks will be correctly positioned in the target posture, but the mapping of the more than 16,000 additional vertices is heavily dependent on the extent of the deformation and the number of landmark descriptors in the local area. For this reason, the robustness of the warping of human figure data is not easily quantified, and the visual results may vary depending on the extent of the deformation and the number of landmarks specified.

These initial tests indicate that thin plate spline algorithm can be used effectively to repositure three-dimensional scan data, enabling the generation of digital human models which match design environments distinctly different from the one in which they were scanned. Using these techniques, a family of scans like those provided by the CAESAR project could be warped and transformed to nearly any position for which adequate landmark descriptors are available.

The results of the between-subject homology mapping indicate that thin plate spline methods may also be used for re-proportioning the data. With these techniques, digital human models for any body shape or landmark homology could be created from a single scan.

For postures and proportions dramatically different from those of the reference, segmentation of the scan results in a warping that more accurately depicts the deformations inherent to each body segment. Additionally, augmentation of the landmark data set to include points near key areas of deformation (e.g. the inside of the elbow joint, the top of the patella, the back of the knee) produces more visually appealing results.

FUTURE WORK

Additional work may be done in order to improve the usability and end results of the thin plate spline analysis as a tool for generating digital human models. Of particular use would be the incorporation of efficient feature extraction methods in order to supplement the number of landmarks used in the analysis. Additionally, the implementation of blending algorithms would be an effective way to smooth edges that appear during the compositing of segmented warped scans.

The number of landmarks in the leg and arm regions could be further augmented through the use of "sliding" landmark methods. Developed by Bookstein [10] and further applied in [11], sliding landmarks allow points on an outline or curve to be treated as landmarks in a Procrustes analysis. The application of this method could greatly enhance the thin plate spline mapping in areas lacking sufficient landmarks.

In order to maximize the accuracy of the deformations described by the analysis or to examine the dynamic changes of enfleshment, future subjects could be scanned with a greater collection of landmark descriptors. By scanning a knee, thigh, the back, or the buttocks with a repeatable landmark grid in place, areas crucial to a particular design or visualization could be warped and repostured to examine seat, tissue, or clothing deformation or used to develop external-contour-deformation algorithms.

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