Estimating human body characteristics under clothing using a statistical body shape model

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Abstract

Whole-body surface scanning technology has revolutionized anthropometry, providing an efficient way to capture detailed body characteristics. Scanning protocols generally require minimally-clad subjects, thus obtaining a body model from a scan of a person with normal clothing still remains a challenge. The current study aims to estimate body shape under clothing or equipment using a statistical body shape model (SBSM). The SBSM was fitted to 100 soldier scans with four different levels of clothing and gear to estimate the body shapes using an inscribed-fitting method. The inscribed-fitting method finds the body shape by finding the maximum body volume available in the body shape space of the model. A rapid fitting method developed in our previous work was used to search a body shape in the body shape space. The result showed the good accuracy in estimating body shape under clothing and gear, with the mean error of 11.2 mm compared to the actual body shape.

Keywords: Inscribed-fitting, Statistical Body Shape Model, Clothing Scans, Anthropometrics

1. Introduction

In the last two decades, whole body surface measurement using three-dimensional scanning technologies has revolutionized applied anthropometry (Park and Reed 2014, Allen et al. 2008, Lu and Wang 2008, Stančić et al. 2013, Yu and Xu 2010). These studies, however, are generally based on minimally-clad scans, thus measuring body characteristics including the body shape from a scan of a person with normal clothing still remains a challenge.

Recently, only a few studies have attempted to estimate body shapes under clothing. Balan and Black (2008) presented a model-based body shape estimate system, which infers nude body shape from a number of multiple images by finding a maximal silhouette-consistent shape. Hasler et al. (2009) takes a similar fitting approach, but the method requires a single laser range scan to estimate the body shape. Recently Guan et al. (2012) presented a method focusing on 2-dimensional models for modeling clothing deformations on the body. These studies all require high computational resources to solve expensive optimization problems.

This paper presents a fast fitting method to estimate the body shape under clothing or equipment. The method is based on a rapid PC-based fitting method (Park et al. 2013) utilizing a statistical body shape model (SBSM). SBSMs used with this method are developed based on laser scans using statistical methods including principal component analysis and multivariate regression (Park and Reed 2014). Because all body shapes generated are within the space of possible body shapes, we leveraged this characteristic to estimate body shapes in scans of clothed subjects using an inscribed-fitting method.

2. Materials and Methods

2.1. Statistical Body Shape Model

The current study used a statistical body shape model (SBSM) based on statistical analysis of scan data obtained from 213 men with wide range of body size. Using the process described in Park and Reed (2015), data from each scan was fitted using a template mesh obtained from the Jack manikin. As a first step in this process, 92 landmarks were estimated and then were used as targets for a non-rigid registration using radial-basis-function interpolation. An implicit surface method was used to complete the template fitting process. Principal component (PC) analysis was conducted on measured landmarks, estimated joint centers, and surface mesh nodes. A total of 200 PC scores were retained from the analysis, which accounts for over 99% of the data variance.

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2.2. Data Source

For the current analysis, whole body scans from 100 soldiers were used. As shown in Figure 1, scanning for the individuals was conducted using a VITUS XXL laser scanner with four different levels of clothing and gear, including minimally clad level (MC), advanced combat uniform level (ACU), personal protective equipment level (PPE), and encumbered with gear level (ENC). The scan data were processed through a pipeline that included hole-filling and decimation to approximately 80k vertices form 170k vertices.

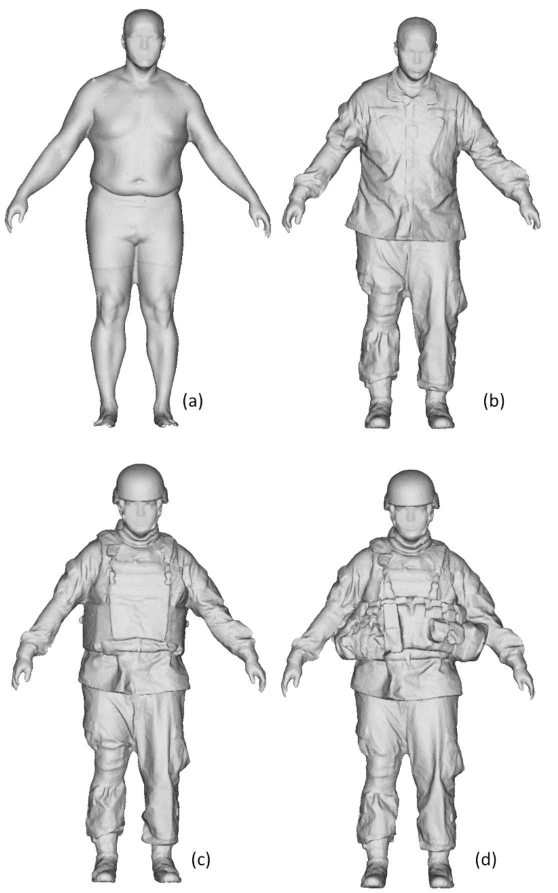

Figure 1: Four different levels of clothing of an individual: (a) minimally clad level (MC), (b) advanced combat uniform level (ACU), (c) personal protective equipment level (PPE), and (d) encumbered with gear level (ENC)

2.3. PC-based Fitting Method

For the rapid measurement of body dimensions, we employed a fast fitting method proposed in our previous study to rapidly find the body shape (Park et al. 2014). The method fits a SBSM to a scan by finding the closest body shape available in the body shape space of the model. Since the body shape of the model is defined by a relatively small number of principal component scores, the closest body shape can be effectively found in this low-dimensional PC space. Once the model is aligned to the target scan, the discrepancy between the two surfaces is computed. A PC-sensitivity matrix, which explains how an increment of each PC score moves the vertices in the Cartesian space, is used to compute the PC scores to fill the computed discrepancy. These PC scores were computed by multiplying the discrepancy vectors by a pseudoinverse of the PC-sensitivity matrix that gives the least-square solution. Figure 2 schematically shows this process.

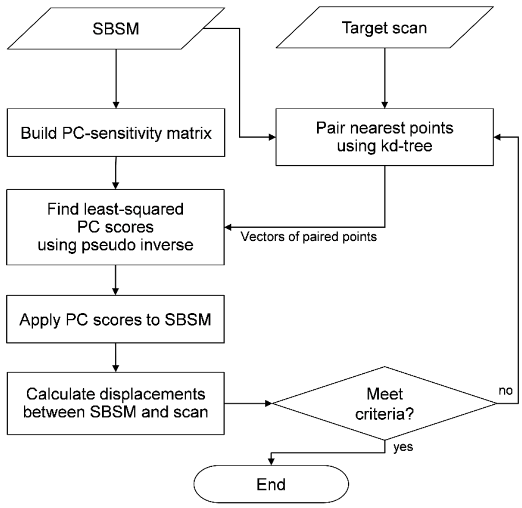

Figure 2: Schematic of PC-based fitting process to fit 3D data in the body shape space of the model

2.4. Inscribed Fitting Method

The inscribed fitting method described in this paper was motivated by the fact that the body shape should lie inside the surface of a clothed body, and at the same time, some parts like face, ankles, and hands of the scan should be close to the actual body shape. This yielded an assumption that an actual body shape is the maximum body volume within the scan surface that is available in the body shape space of the model. Conceptually, this is similar to finding an inscribed sphere in a polygon.

The inscribed fitting method consists of the following steps:

1. Compute an initial PC score vector $\boldsymbol{p_0}$ by fitting the SBSM to a target scan using the PC-sensitivity matrix.
2. Find vertices of the model **outside** the target scan surface.
3. Build a sub-sensitivity matrix by keeping the columns only related to the outside vertices from the PC-sensitivity matrix.
4. Compute direction vectors from the outside vertices to the closest points of the scan using a kd-tree.
5. Compute a PC vector $\boldsymbol{p_i}$ by multiplying by a pseudo-inverse of the sub-sensitivity

matrix by the direction vectors to move the outside vertices to the scan surface.

6. Update the PC score vector $\boldsymbol{p}_0 = \boldsymbol{p}_0 + \boldsymbol{p}_i$ and apply $\boldsymbol{p}_i$ to the model.

7. Go to step 2 until a criterion is met.

Figure 3 illustrates the outside vertices and the direction vectors. The outside vertices were found using the normal vectors at each point of the target scan. A sub-sensitivity matrix for these vertices was extracted from the original PC-sensitivity matrix by taking the vectors corresponding to the outside vertices. Conceptually, while the sub-sensitivity matrix explains how the increments of PC scores affects these vertices, and the inverse of the matrix allows for estimating the increments of PC scores to move the vertices to certain target points. Thus, we multiplied a pseudoinverse of the matrix by the direction vectors to get the PC score increments to move the outside vertices onto the target scan surface. Since the pseudoinverse provides a least-square solution, a few iterations are needed to get the most of the outside vertices inside the measured surface mesh.

Figure 4 shows the results of each inscribed fitting process for a sampled PPE scan. While the initial fitting gives overall body shape and well-matched posture this is still a larger body shape than the actual one due to the clothing (Figure 4(a)). By iterating the process of pushing the outside vertices onto the target surface, we can get the maximum body shape that lies inside the scan surface. Experimentally, about 3 to 15 iterations result in good estimation of the body shape, depending on the level of clothing. For example, for ENC scans, the highest level of gear, about 10-12 iterations were performed to estimate the underlying body shapes.

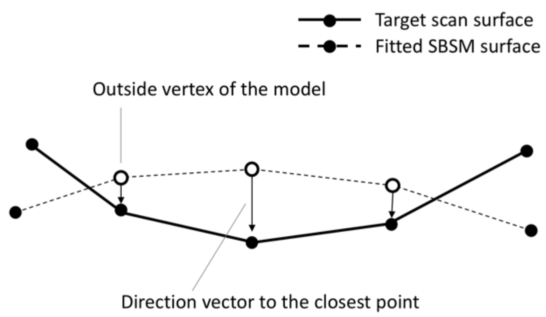

Figure 3: Model vertices located outside the scan surface and direction vectors to move the outside vertices onto the scan surface

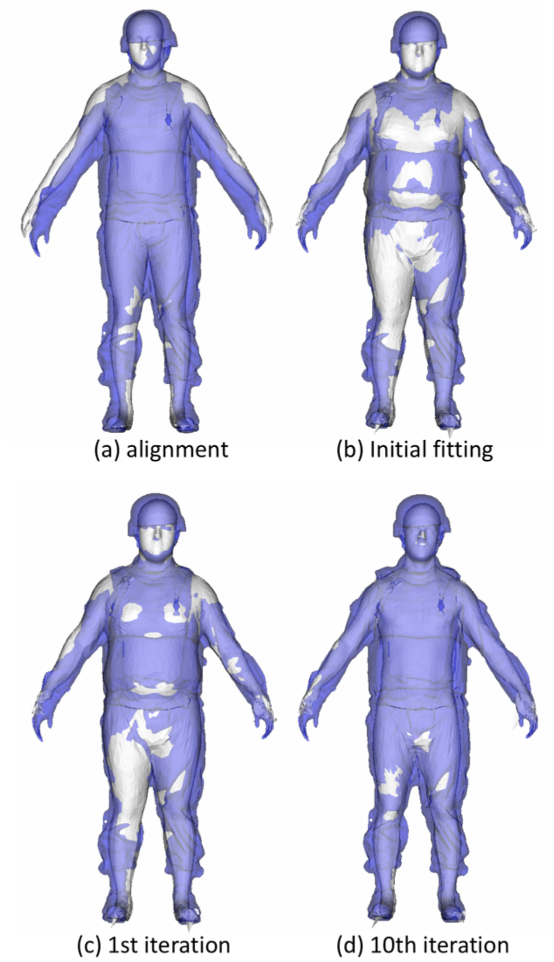

Figure 4: Effect of iterations on fitting results of a SBSM (white) to a sample scan (blue)

3. Results

The SBSM was inscribed-fitted to 300 scans of ACU, PPE, and ENC levels of 100 male soldiers. Figure 5 shows examples of the fitted results at each level. Each row shows the target scan (white) and the estimated body shape (yellow) using the inscribed fitting method. Figure 5(d) shows a quantitative comparison between the estimated body shape and the minimally-clad scan of the same soldier. The mean absolute distances between the two surfaces were computed at each vertex and coded with the color in red (50 mm) to blue (0 mm). Due to differences in extremity postures between the scans, only the torso area was evaluated quantitatively.

In Figure 6, the mean errors at each vertex across all the scans were color-coded on a mean body shape. For the ACU scans, the mean error was 11.1 mm, 95^{th} %tile error was 17.1 mm, and the root-mean-square-error (RMSE) was 11.7 mm. For the PPE and ENC scans, the mean errors were 11.0 mm, 11.6 mm, 95^{th} %tiles were 15.0 mm, 16.5 mm, and RMSEs were 11.5 mm and 12.0 mm, respectively.

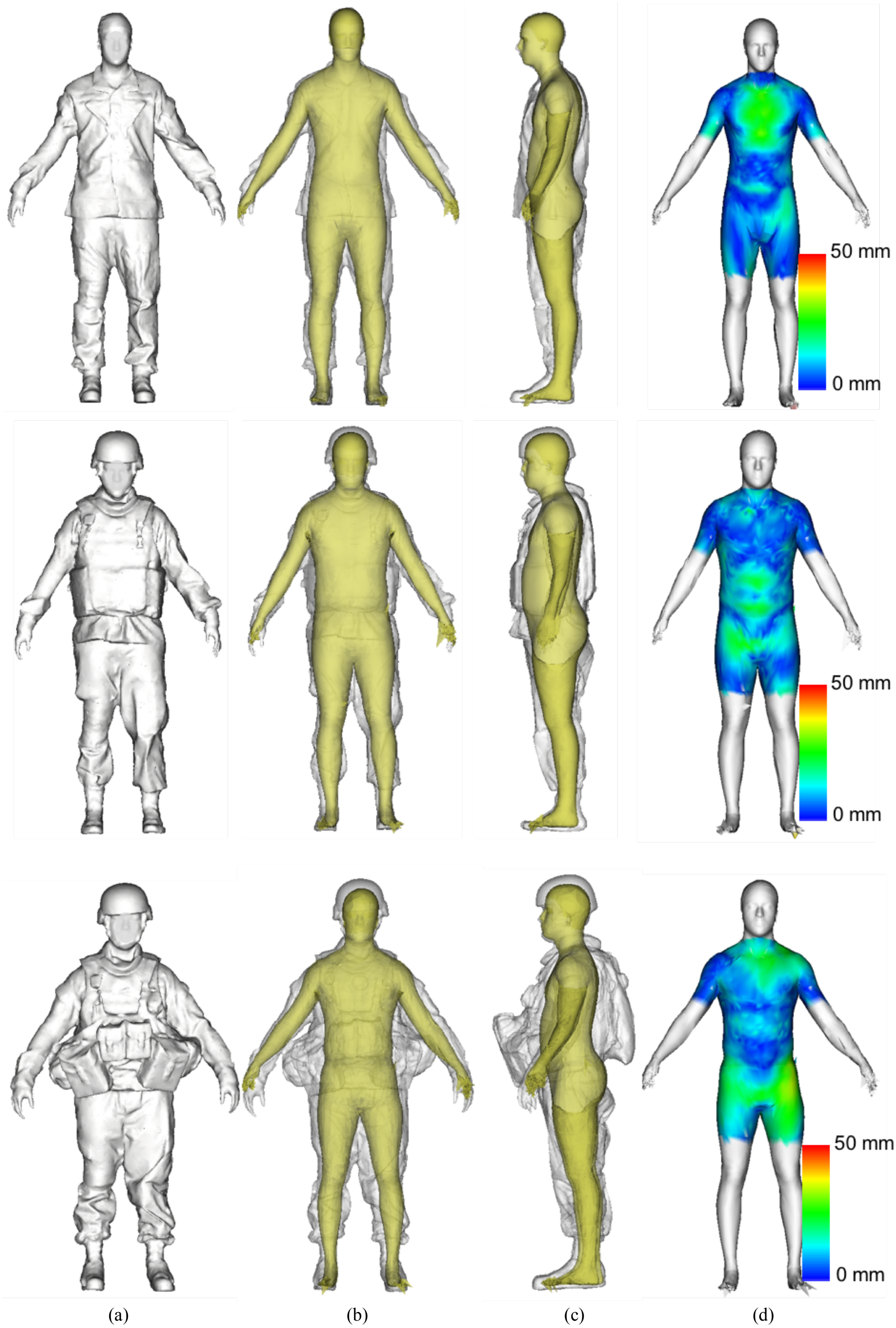

Figure 5: Comparison of original target scans and inscribed-fitted manikins: (a) target scan data of each gear level (top: MC, middle: PPE. bottom: ENC), (b) and (c) the front and side view of comparison between target scans (white) versus fitted manikins (yellow), (d) quantitative comparison between the fitted body shapes and the minimally-clad scans of the same individuals. Mean absolute errors are coded with colors.

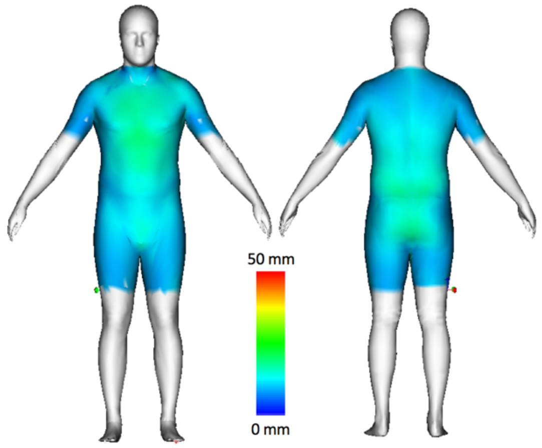

Figure 6: Mean error distribution was color-coded on a mean body shape.

The fitting time was under two seconds per scan on average on a typical laptop computer (I7 3.4GHz CPU with 16 GB RAM). Experimentally, the number of iterations required was 3 ~ 6 for ACUs scans, 8 ~ 10 for PPEs, and 10~12 for ENCs.

4. Discussion

This paper presented an inscribed fitting method to rapidly estimate body shape and body dimensions under clothing and gear. The method showed fast performance and convergence, regardless of what level of clothing and gear might be, without solving expensive optimization problems. The vertex error values were fairly small, but relatively larger errors were observed in the chest, abdomen, and buttocks, reflecting the fact that the method is only moderately successful in determining torso dimensions under the clothing and gear.

The estimated body shapes in this study can be used to extract the gear and protective equipment from the soldier scans as shown in Figure 7. However, the applications of this method are not limited in this particular area. This can be applied broadly to any situation in which objects are in contact with a body that is in a controlled pose. For example, this can be applied in generating a subject-specific avatar of a clothed person using low-cost depth cameras (Park et. al. 2014) and could be used to estimate body shape for people sitting on automotive seats.

In addition to the body shape, a number of standard anthropometric values, body surface landmarks and joint locations that are embedded in the SBSM can be effectively obtained from a fitted body shape model. Park et al. (2014) showed good accuracy in predicting overall body dimensions ($R^2 > 0.92$) using this approach. Note that the statistical body shape model used in this study incorporates 16 anthropometric values, 78 body surface landmarks, and 18 joint locations as well as the body shape.

The major limitation of this method is that the body shape model we used in this study does not incorporate articulation, so that only a scan with a particular standing posture can be used. However, we are currently developing a fully-posable body shape model that will enhance this method to estimate arbitrary postures.

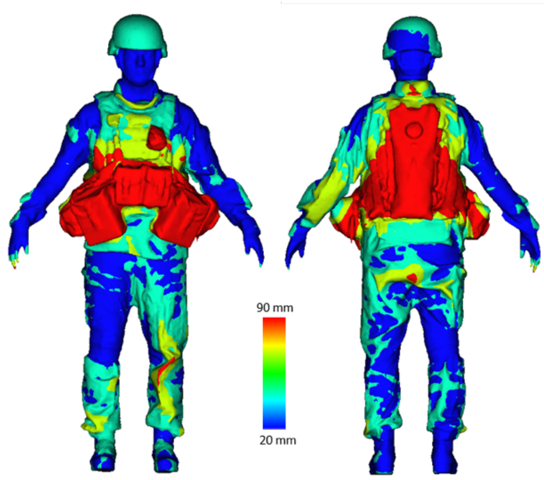

Figure 7: Analysis for extracting gear and equipment geometries. These geometries can be effectively extracted from a standing-soldier scan by comparing the estimated body shape.

The other limitation is that the inscribed-fitting method estimates the body shape based on the clothing surface. Thus, if the clothing and the equipment surfaces provide less information about the body shape (e.g., astronaut in a space suit), the estimation accuracy is likely to be lower. However, thickness information for equipment or clothing could be used to improve estimation in these cases.

5. Conclusion

This paper demonstrated a fast fitting method to estimate the body shape under clothing or equipment. This inscribed fitting method can be applied to equipment extraction, apparel design, seat optimization and fast subject-specific manikin modeling.

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