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Three-dimensional (3D) analysis of knee shape for designing a knee-pad

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Abstract

This paper presents an approach to register a large number of adult 3D surface whole body scans and segment the knee region to generate a knee-specific dataset.We then applied shape analysis methods to the segmented surfaces to obtain major knee shape variation of the population. We analyzed 2069 male scans and present the first 5 significant shape modes of the knee in standing and bent poses. The knee models were used to design a knee-pad for the US Army.

*Keywords:*3D scan registration; Principal component analysis; Knee shape

1. Background

Designing personal protective equipment for a population requires an understanding of the shape variation of the area to be protected. Developing a suitable shape data set has many challenges. First, a large-scale 3D scan database is required for population-level analysis. Second, most large databases obtain scans in a standardstanding positionand one or two other positions [1,2]. Given the near infinite number of possible functional positions a person may take, scanning a large number of people in multiple poses for different product designs is impractical. Thus, it is desirable to have a means to re-align scans into poses appropriate for the product under development. Third, performing a population-level shape analysis requires all scans be in correspondence. That is, vertices in scan

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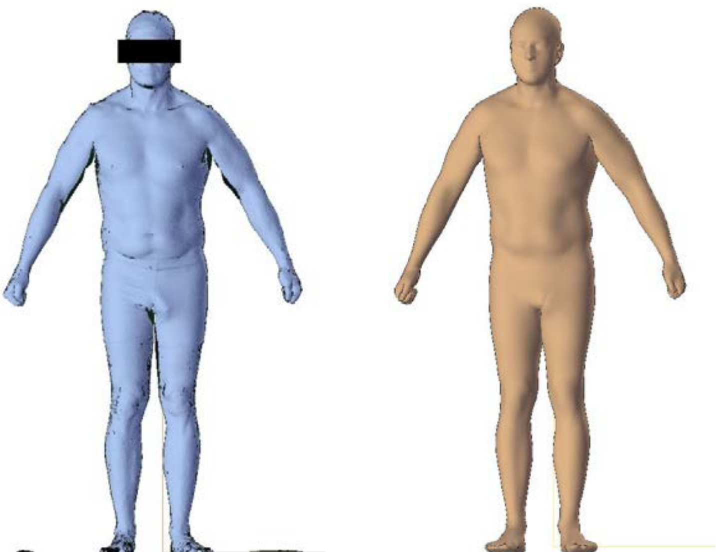
meshes must be in homologous positions across the data set. Here we present anapproach to facilitate 3D shape analysis of straight and bent knees from 3D scans collected in US Army's 2013 Anthropometric Survey (ANSURII) [3] for kneepad design.

2. Methods

A primary difficulty in shape analysis of 3D body scans is assuring that each surface vertex is in correspondence across all scans. To achieve correspondence, a template matching approach is most promising [4, 5, and 6]. The template matching method not only makes surface correspondence, but also fills holes and decimates the raw surfaces. We employedHirshberg et al's method [5, 6] to align 6000 male and female scans from the ANSURII survey into a uniform mesh structure. With this uniform mesh structure, the same segment/region of the body surface shares the same vertex indices. With surface correspondence it is possible to identify a surface regionof interest by selecting its vertices/triangle faces from the single template mesh and then transferthe selection to other scans. This one-to-many segmentation process enables us to quickly generate a large sample for later statistical analysis, such as principal component analysis (PCA).

Although the template surface reduced mesh density relative to the original scan, its mean surface distance error to the raw surface is very small (less than 1mm) after alignment.The small error between derived and original scan shows the lower resolution surface afaithful representation of the original shape. Figure 1 shows a raw scan and its aligned surface.

A knee-pad provides protection when moving in a more-or-less upright position (walking and running) as well as when kneeling. Therefore it is desirable to obtain the shape variation of bent knees. Obtaining a large-scale scanned population in a kneeling position is impractical, if suitably posed scans do not exist in the scans database. An alternative solution is to morph existing standing "A-pose" scans (Figure 1) into the pose required such as kneeling. This was achieved through the application of a SCAPE model [7] and a co-registration process developed by researchers at Brown University and the Max Planck Institute [5, 6]. The method first aligned a deformable template to a scan in the kneeling pose. The template's kneeling pose transformation parameters were then applied to the template aligned A-posescans. In this way a template aligned A-pose surfaces were re-aligned to a kneeling pose. Taken together, A-pose and re-aligned bent knee data provided the basis for knee shape analysis to support the knee-pad design. Figure 2 shows the pose re-alignment results.



a) b)

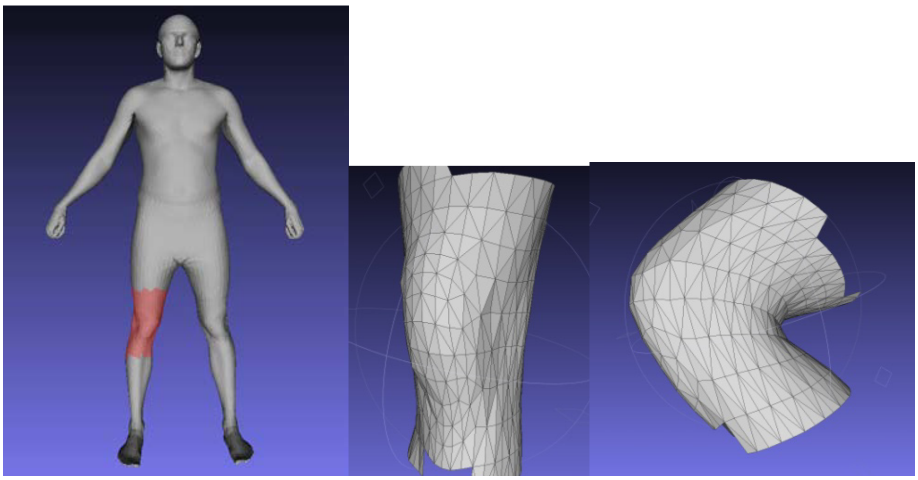
Fig. 1.a) raw scan, b) template surface aligned to the raw scan.

a)b)

Fig. 2.a) Kneeling scan, b) template matching for parametertransfer.

Knee segmentation was only performed onthe reference standing pose once. The knee region was manually marked on a template mesh which identified the vertex indices for segmentation. The indices were then transferred to all standing and kneelingposes to obtain the knee segments. Figure 3 shows the segmentation process. As noted above, this one-to-many segmentation capability is an importantbenefit of having the scans in correspondence.

From the above procedure, we obtained 2069 male subject’s knee surfaces in standing and kneeling poses. Each knee surface contained 394 xyz coordinates. A MATLAB program [8] was written to performprincipal components analysis on these data.



a) b)

Fig. 3.a) painted knee section, b) knee segment in standing and kneeling pose.

3. Results

The shape analysis showed that the top 12 principal components (PCs) accounted formore than 95 percent of knee shape variation in standing and kneeling poses as shown in Figure 4. However, shape variation represented by each PC is pose dependent. In figure 5and figure 6we plotted knee shapes from the first five PCs, representing 85% variation ofstanding and kneeling pose analyses, respectively. In the figures, the red mesh is the mean shape, the yellow mesh is plus three times the standard deviation (+3D) and the blue mesh is minus three times the standard deviation (-3D). In the standing pose, the first PC represents circumferential variation of the knee segment with an overall increase in lower thigh thickness.The second PC represents both circumferential and overall length increase from -3D to +3D extreme shape. The third PC represents shape variation both in length and in straightness of the leg. The fourth and fifth PCs represent tilt angle of knee in posterior and lateral directions, respectively.

The shape variation in the bent knees is more difficult to describe. The first PC represents an overall length and circumferential changes. The second PC shows the bending angle changed at the back of knee while the front angle almost kept constant. The third PC shows thickness change at the upper knee section with fixed bending angle. The fourth PC shows some upper knee section growth towards inside of leg. The fifth PC has two dominant (though small) shape variations: first is a rotational/tilted amount of low leg in outwards direction, second is the degree of outstanding knee cap.

Standing knee	EigenValues	var-pcent	accuVar	Bent knee	EigenValues	var-pcent	accuVar
PC1	14196.113643	0.359189	0.359189	PC1	0.007678	0.462627	0.462627
PC2	9679.075947	0.244899	0.604089	PC2	0.004131	0.248895	0.711522
PC3	6255.736883	0.158282	0.762371	PC3	0.000991	0.059682	0.771204
PC4	3269.990784	0.082737	0.845108	PC4	0.000824	0.049620	0.820824
PC5	1151.457412	0.029134	0.874242	PC5	0.000494	0.029763	0.850587
PC6	866.666881	0.021928	0.896170	PC6	0.00039	0.023524	0.874111
PC7	662.958215	0.016774	0.912945	PC7	0.000337	0.020329	0.894439
PC8	569.668326	0.014414	0.927358	PC8	0.000262	0.015765	0.910205
PC9	502.060485	0.012703	0.940061	PC9	0.00022	0.013234	0.923439
PC10	361.345666	0.009143	0.949204	PC10	0.000195	0.011739	0.935178
PC11	284.321129	0.007194	0.956398	PC11	0.000174	0.010458	0.945636
PC12	209.327283	0.005296	0.961694	PC12	0.000112	0.006757	0.952394

Fig. 4.Eigenvalues, their percentage of varianceand accumulated percentage of variance in standing and bent knee shapes (note: eigenvalue scale difference in the above two tables is due to data unit difference).

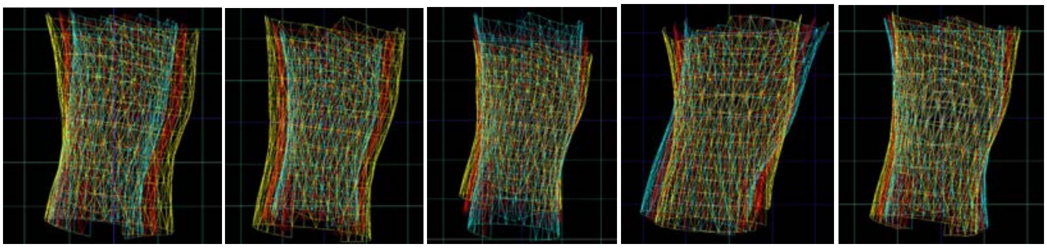


Fig.5.Standing knee shape variation.

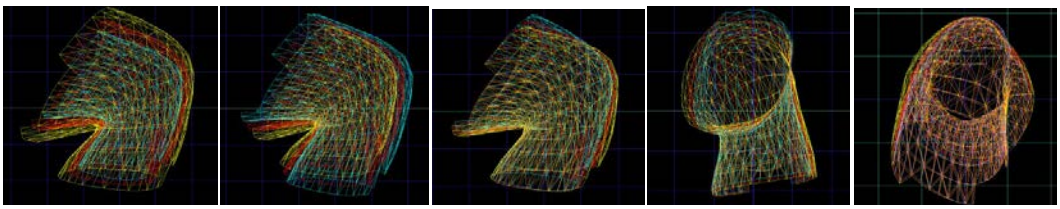


Fig. 6.Bentknee shape variations.

After the above shape analysis process, straight and bent knee geometry was provided as non-uniform rational b-spline (NURBS)models for knee-pad prototype design in a CAD environment. Creating a virtual prototype around representative knee size and shape in two important poses for knee-pad use yielded a more mature prototype. First, as a one-size-fits-all item, having awide range of knee geometry allowed us to examine how the pad accommodated large and small knees. Second, with straight and bent knees we were able to visualize securing strap placement and up/down adjustability. Last, the shape of hard materials was contoured to match knee curvature. Physical knee-pad prototypes were 3D printed from CAD parts to check integration with soft materials and with the trouser insert pocket.

4. Conclusions

Combining the power of a large scale 3D database and the co-registration process, we were able to re-align 2069standing scans into a kneeling position and obtain 3D scan data in a new functional pose to support the design of a new Army knee-pad. This approach may be used to generate shape models for other productsthat target particular body regions and poses. For example, we provided male and female whole leg+foot geometry for a product that runs from hip to ankle.

Our analysis of knee shape and the selection of representative models provided knee geometry from real individuals. Notice that no standard anthropometry was used in analysis or in the generation of knee shapes, the knee pad was designed from geometry alone. Although standard anthropometry has its place in product design, more often than not anthropometry is used to generate geometry. Our approach utilizes statistically relevant geometry from the outset, which we believe is preferable over generating body shapes from anthropometry.

References

[1] Hotzman, J. Gordon, C.C., Bradtmiller, B., Corner, B.D., Mucher, M., Kirestensen, S., and Paquette, S.: 2011 "Measurer's Handbook: US Army and Marine Corps Anthropometric Surveys, 2010-2011.*Technical Report NATICK/TR-11/017*, US Army Soldier Systems Command, Natick Research, Development and Engineering Center.

[2] Robinette, K., Blackwell, S., Daanen, H., Boehmer, M., Fleming, S., Brill, T., Hoeferlin, D., Burnsides, D., 2002, “Civilian American and European Surface Anthropometry Resource (CAESAR) Final Report, Volume I: Surmmary”, *Technical Report AFRL-HE-WP-TR-2002-0169*, United States Air Force Research Laboratory

[3] Gordon, Claire C., Blackwell, Cynthia L., Bradtmiller, Bruce, Parham, Joseph L., Barrientos, Patricia, Paquette, Stephen P., Corner, Brian D., Carson, Jeremy M., Venezia, Joseph C., Rockwell, Belva M., Mucher, M., and Krietensen, S., 2014: 2012 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics. *Technical Report NATICK/TR-15/007*, US Army Soldier Systems Command, Natick Research, Development and Engineering Center.

[4] Allen, B., Curless, B., Popović, Z. (2004), “Exploring the space of human body shapes: data-driven synthesis under anthropometric control”, SAE Digital Human Modeling, 2004.[5] Hirshberg, D. A., Loper, M., Rachlin, E., Tsoli, A., Weiss, A., Corner, B., Black, M. J., 2011 “Evaluating the automated alignment of 3D human body scans**”** *2nd Int. Conf. on 3D Body Scanning Technologies*, Lugano, Switzerland, pp. 76-86, Oct. 25-26, 2011.

[6] Hirshberg, D. A., Loper, M., Rachlin, E., Black, M. J., “Coregistration: Simultaneous Alignment and Modeling of Articulated 3D Shape”, Computer Vision – ECCV 2012, Lecture Notes in Computer science Vol 7577, 2012, pp 242-255.

[7]Anguelov, D., Srinivasan, P., Koller, D., Thrun, S., Rodgers, J., Davis, J.: “SCAPE: Shape Completion and Animation of People”, ACM ToG. 24 (2005), pp 408-416.

[8] MATLAB and Statistics Toolbox Release 2014, The MathWorks, Inc., Natick, Massachusetts, United States.