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Crotch detection on 3D optical scans of human subjects

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Abstract

Three-dimensional optical devices are relatively inexpensive and can rapidly acquire body surface scans. Therefore, they can be used as an efficient tool for automatically obtaining landmarks and anthropometric measurements. In this study, we develop an algorithm called DeCIMA (Detecting the Crotch In Mesh Analysis). DeCIMA automatically finds the crotch, as one of the fundamental landmarks on 3D human optical scans. DeCIMA presents a solution for finding the crotch-location even in challenging cases where the subjects' thighs are connected. We test DeCIMA on 225 scans obtained from 75 human subjects using three different scanners. We compare the crotch height obtained by DeCIMA with the crotch height reported by the proprietary software of the 3D optical scanners. Results show that DeCIMA improves crotch detection and can correctly detect the crotch even for subjects with connected upper thighs.

Keywords— Crotch height, 3D optical scans, anthropometry, landmark detection

Introduction

Anthropometric measurements are widely used for quantifying body size and shape with applications ranging from clothing design to clinical assessments of health risk factors [1–5]. Three-dimensional (3D) optical devices can rapidly acquire body surface scans [6–8]; however, different scanners provide different sets of landmarks and anthropometric measurements and the measurements provided are also often inconsistent between devices [7–9]. Moreover, although most of the provided measurements are fairly accurate for an average subject, however, recent studies have shown system measurement limitations, such as discrepancies in landmarking [8].

The crotch is a fundamental landmark in landmark detection and automatic calculation of anthropometric measurements [10]. In this study, we develop an algorithm, called DeCIMA (Detecting the Crotch In Mesh Analysis), that automatically finds the crotch on a 3D human optical scan. Although finding the crotch may not be very complicated for slim subjects (Fig. 1-a), it can be challenging for subjects whose thighs are connected as shown in Fig. 1-b. For such subjects, a simple crotch-finding approach will misspecify the crotch as the point where the thighs are connected (red cross in Fig. 1-b) while the actual location of the crotch is higher (as marked by the green circle in Fig. 1-b).

Proprietary software provided by some 3D optical scanners detect the location of the crotch on human scans. However, the reported crotch heights can be highly erroneous for some subjects. In this study, we present DeCIMA. DeCIMA is an algorithm which improves crotch-finding through two steps. First, an initial estimation of the crotch-location is obtained using a max-min approach. Then, the crotch-location is modified by taking cross-sections of the 3D scan around the initially estimated crotch-location and evaluating the extreme points of its convex-hull.

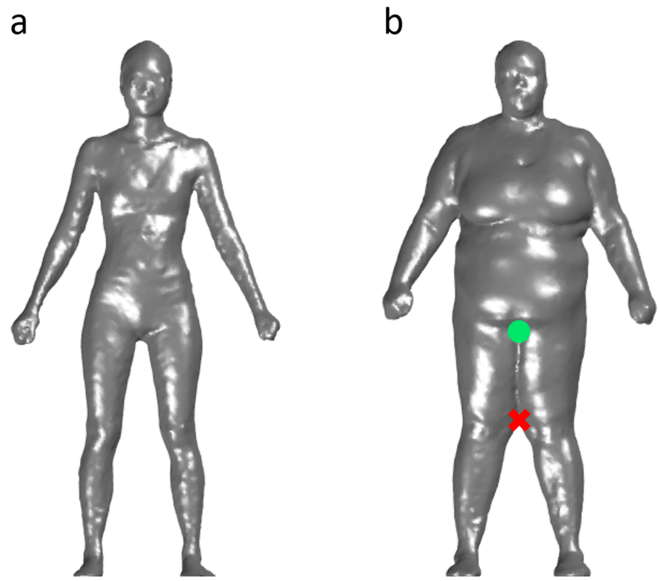

Figure 1. *3D optical scan of a subject whose thighs are not connected (a), and a subject whose thighs are connected (b).*

We compare the crotch height obtained by DeCIMA with the crotch height reported by the proprietary software of three different 3D optical scanners. Results show that DeCIMA correctly detects the crotch even in cases which the subjects' thighs are connected.

Methods

Subjects

A sample of 75 adult men and women were asked to arrive at the laboratory and change into form fitting shorts and, if female, a sports bra. Subjects with hair that extended below their chin were asked to wear a swim cap. The subjects were scanned by three different 3D optical scanners (Styku [Styku, Los Angeles, CA],

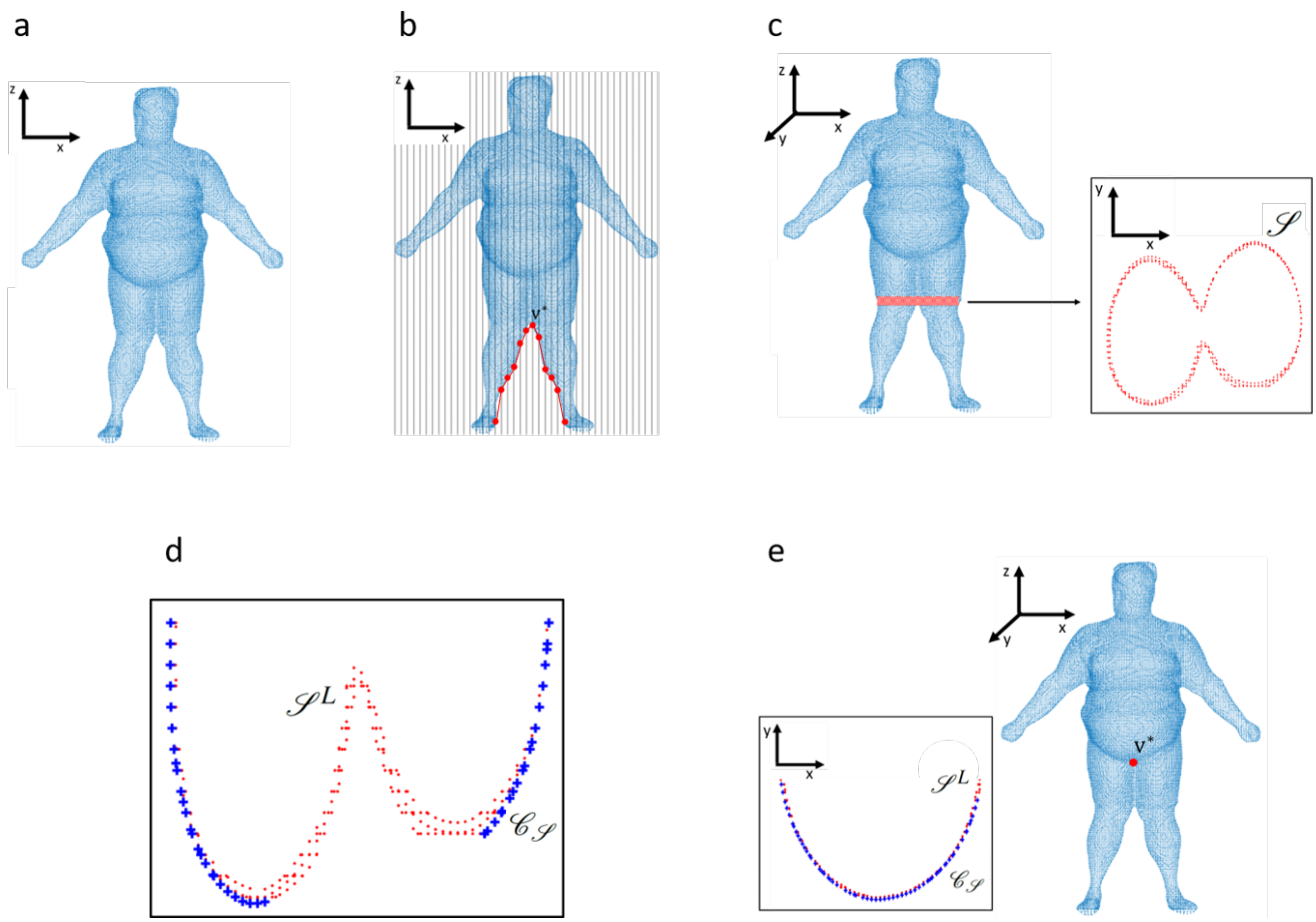

Figure 2. *Pictorial representation of how DeCIMA finds the crotch on a 3D optical scan of a human subject.*

Proscanner [Fit3D, Redwood City, CA] and SS20 [SizeStream, Cary, NC]). For all scans, subjects were asked to stand with their hands in a downward V position.

Scanners

The Proscanner, Styku and SS20 scanners, all use similar inexpensive infrared sensors. The Proscanner uses three stationary cameras that are aligned vertically on a column. During the image capture, the subject holds onto adjustable handles while standing on a turntable that rotates for about 40 seconds. The Styku scanner uses a single stationary camera on a tower. This scanner does not have adjustable handles and while scanning the subject stands on a turntable that rotates for about 30 seconds. The SS20 uses twenty cameras positioned at five different heights along four vertical columns. The subject stands stationary in the center of the columns holding on to handles for the scanning duration which is about 4 seconds.

Algorithms

Notation

The data for each 3D scan contains a triangular mesh represented by a list of vertices and a list of faces. Let N and M represent the number of vertices and faces, respectively. Let $\boldsymbol{v}$ denote an $N \times 3$ array containing all vertices where, each row consists of the x, y, z coordinates of each vertex. Let $\boldsymbol{f}$ denote an $M \times 3$ array containing all faces where, each row consists of the vertex numbers of the three vertices generating each face. Let $\mathscr{S}$ represent a cross-section of an avatar, $\mathscr{S}^L$ the lower half of $\mathscr{S}$, and $\mathscr{C}_{\mathscr{S}}$ the extreme points of the convex hull of $\mathscr{S}$.

Finding the crotch

For finding the crotch, we first outline an arch shape and then find the peak of that outline as explained in *step 1* of Algorithm 1. The simple procedure in *step 1* of Algorithm 1 is not sufficient for finding the crotch in cases where the subject's upper thighs connect such as in Fig. 2-a. *Step 2* of Algorithm 1 is designed to handle this complexity. In this step, the crotch-location is modified by evaluating the extreme points of the convex-hull of avatar cross-sections obtained at a neighborhood of the initially estimated crotch-location.

Avatar cross-section Obtaining the cross section of an avatar requires intersecting a plane with the avatar. Since $\boldsymbol{v}$ is a discrete set, the intersection of $\boldsymbol{v}$ with a plane may not even include any vertices. To ensure that an adequate number of vertices are chosen for defining a cross-section, we propose the procedure presented in Algorithm 2, where, we first find all faces in $\boldsymbol{f}$ that

Input: List of faces and vertices; $\boldsymbol{f}$, $\boldsymbol{v}$
Output: Coordinates of crotch: $[x^\star, y^\star, z^\star]$

begin
- ***Step1: initial estimation:***
- 1) Project the 3D avatar on the xz-plane. (Fig. 2-a).
- 2) Divide projected space in vertical bands (Fig. 2-b).
- 3) Find vertex with mininum z value in each band (red vertices in Fig. 2-b).
- 4) Set initial crotch estimate ($v^\star = [x^\star, y^\star, z^\star]$) as the vertex with maximum z-value among red vertices.
- ***Step2: adjusting the initial estimate:***
- cnd = 'true'.
- **while** *cnd* **do**
  - 1) Take horizontal slice of 3D avatar at $z = z^\star$
  - 2) Project slice on xy-plane to get $\mathscr{S}$ (Fig. 2-c).
  - 3) Let $\mathscr{S}^L$ denote lower half of $\mathscr{S}$ as in Fig. 2-d.
  - 4) Define $\mathscr{C}_{\mathscr{S}}$ as extreme points of the convex-hull of $\mathscr{S}^L$ (Fig. 2-d).
  - **if** *$\mathscr{S}^L$ and $\mathscr{C}_{\mathscr{S}}$ are the same* **then**
    - cnd = 'false' (Fig. 2-e),
  - **else**
    - Increase $z^\star$ by a small increment Δz.
  - **end**
- **end**

end

Algorithm 1: The algorithm for finding the crotch on a 3D optical scan of a human subject.

intersect with the plane. Then we take the vertices of those faces and project them onto the plane. This gives us the projection of the vertices that are relatively close to the plane. We then define a cross-section, $\mathscr{S}$, to be the set of the projected vertices.

Note that, since a cross-section ($\mathscr{S}$), is defined by a set of discrete points, the convex hull of $\mathscr{S}$ would be a polygon and so $\mathscr{C}_{\mathscr{S}}$, which is the set of extreme points of the convex hull of $\mathscr{S}$, will be the set of the polygon.

Implementation

Matlab (Mathworks, Natick, MA) was used to implement and test DeCIMA. The performance of DeCIMA is compared against the performance of the proprietary software of the 3D optical scanners. To quantify the performance of automatic crotch detection, we use automatically calculated crotch heights.

A human observer was asked to manually specify the location of the crotch on each 3D scan and report the resulting crotch height. The crotch height reported by the human observer is used as the reference with which automatic crotch heights are compared. Linear regression and Root Mean Sqaure Error (RMSE) are used as the evaluation criteria.

Numerical Results

Linear regression and RMSE results are presented in Table 1 for crotch heights calculated using DeCIMA as well as crotch heights reported by the proprietary software of the scanners. For linear regression results, both R^2 values and the best fit linear model are presented in Table 1. These results are given for the Proscanner, SS20, and Styku scanners. However, the proprietary software of the Styku scanner does not provide crotch height measurements and the cells of the table corresponding to Styku's proprietary software contain Not Applicable (NA). Nevertheless, we have reported the results for the crotch heights calculated by DeCIMA using the scans obtained from the Styku scanner, in order to provide comparison among the different scanners.

Input: $\boldsymbol{v}$: List of vertices, $\boldsymbol{f}$: list of faces, plane $\mathscr{P}$.
Output: $\boldsymbol{v}_p$: Projection of vertices close to $\mathscr{P}$ onto $\mathscr{P}$.

begin
- Rotate $\mathscr{P}$ such that it is parallel to the xy-plane.
- Rotate $\boldsymbol{v}$ with same rotation.
- Let z_p be the z-value of rotated $\mathscr{P}$.
- Initialize $\boldsymbol{v}_p$ to be an empty set of vertices.
- **for** *each face in $\boldsymbol{f}$ (denoted f_i)* **do**
  - Let v_1, v_2, v_3 be the three vertices of f_i.
  - Let z_1, z_2, z_3 be the z-values of v_1, v_2, v_3.
  - Define $\text{cnd}_1 = (z_1 \geq z_p \ \& \ (z_2 \leq z_p \text{ or } z_3 \leq z_p))$.
  - Define $\text{cnd}_2 = (z_2 \geq z_p \ \& \ (z_1 \leq z_p \text{ or } z_3 \leq z_p))$.
  - Define $\text{cnd}_3 = (z_3 \geq z_p \ \& \ (z_1 \leq z_p \text{ or } z_2 \leq z_p))$.
  - **if** *cnd_1 or cnd_2 or cnd_3* **then**
    - Calculate projection of v_1, v_2, v_3 on $\mathscr{P}$.
    - Add the projections to the set $\boldsymbol{v}_p$.
  - **end**
- **end**
- Remove duplicates of $\boldsymbol{v}_p$.

end

Algorithm 2: The algorithm for obtaining a cross-section of a 3D human body scan.

Table 1: Comparison of the crotch estimates of DeCIMA and the proprietary software for the different scanners.

Scanner	Software	R^2	Best Fit Linear Model	RMSE (mm)
Proscanner	Proprietary	0.76	$y = .90x + 76$	23
	DeCIMA	0.81	$y = .95x + 29$	20
SS20	Proprietary	0.67	$y = .69x + 233$	30
	DeCIMA	0.73	$y = .75x + 189$	23
Styku	Proprietary	NA	NA	NA
	DeCIMA	0.74	$y = .86x + 90$	30

From the results in Table 1 we can see that for both, the Proscanner and the SS20 scanner, DeCIMA achieves higher R^2 values than the estimates from the scanners. This means that the crotch height values calculated by DeCIMA are more consistent than the values reported by the proprietary software. Moreover, for both scanners, the RMSE for DeCIMA is lower than the RMSE for the proprietary software. This indicates that the crotch height values obtained by DeCIMA are more accurate than the values reported by the proprietary software, i.e., they are closer to the values reported by the human observer.

In addition to evaluating DeCIMA, the results reported in Table 1 also provide insight regarding the quality of the scans provided by each scanner for crotch detection. The crotch heights obtained from the SS20 and Styky scanners are similar in their consistency and RMSE. However, the crotch heights obtained from the proscanner are more consistent and more accurate than the crotch heights obtained by SS20 and Styku.

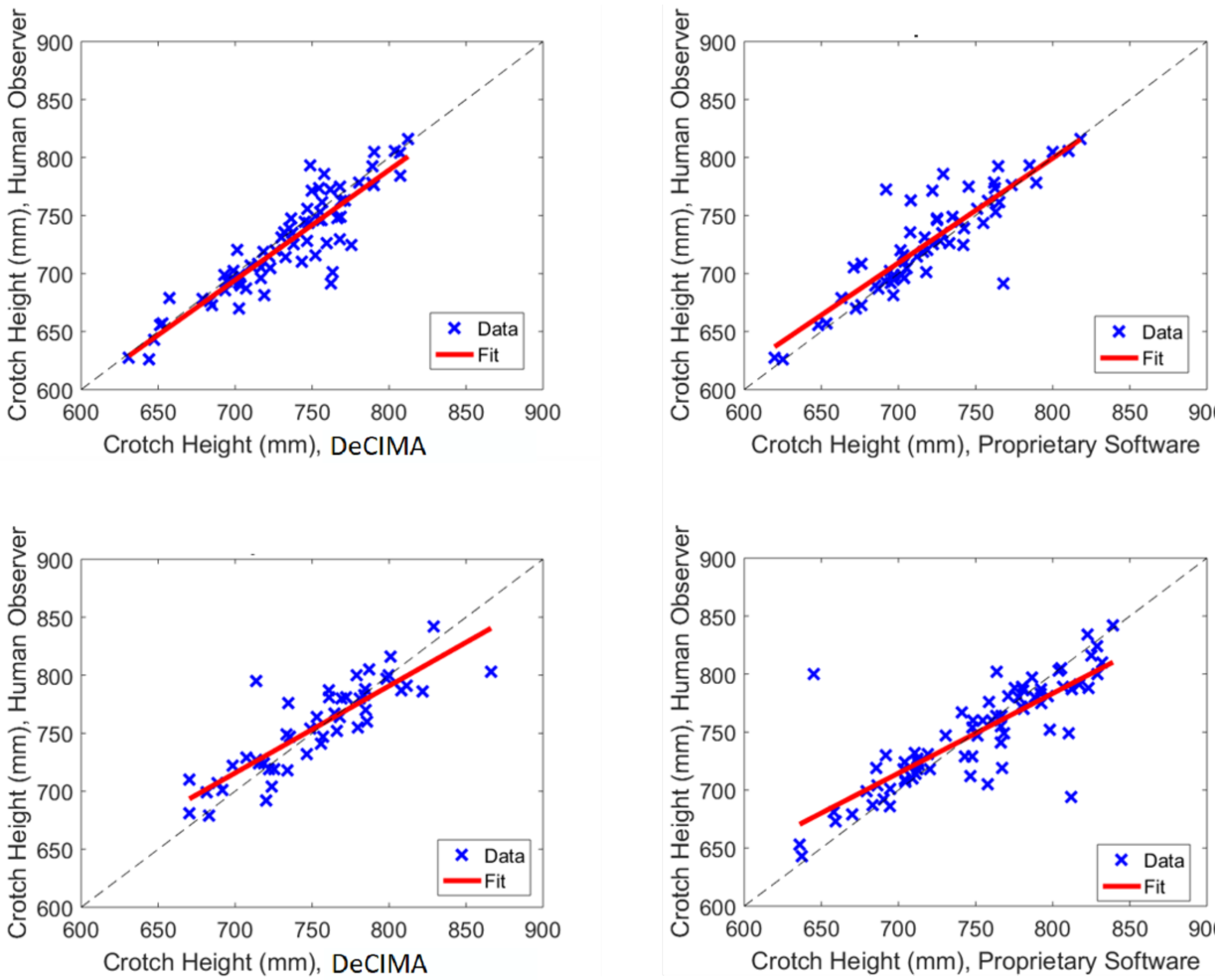

Figure 3. *Linear regression results, top row: results from the Proscanner, bottom row: results from the SS20 scanner, right column: results from crotch height measurements given by proprietary software, Left: results from crotch height measurements calculated using DeCIMA.*

In Fig. 3, the plots for the best fit linear model that is used to compute the R^2 values are shown for both proscanner and SS20. Moreover, in Fig. 4, the worst underestimation and overestimation of the crotch height value is presented as well as a case of perfect estimation for a subject whose thighs are connected. These figures show the 3D scan along with a solid red line showing where the crotch height is determined by the human observer and a dashed blue line showing where the crotch height is determined by DeCIMA.

Conclusion

The crotch is a fundamental landmark for automatically detecting landmarks and calculating anthropometric measurements. In this paper, we proposed an algorithm, called DeCIMA that automatically finds the crotch on a 3D human optical scan. We compare the crotch heights obtained by DeCIMA with the crotch heights reported by proprietary software provided by the scanner manufacturers. Crotch heights reported by a human observer were used as the reference to evaluate automatic crotch height calculation. Linear regression and RMSE results were reported. The results showed that the crotch heights calculated by DeCIMA are more consistent and more accurate than the crotch heights reported by the proprietary software. Moreover, figures were presented to show that DeCIMA is able to correctly detect the crotch even in challenging cases where the subjects' thighs are connected.

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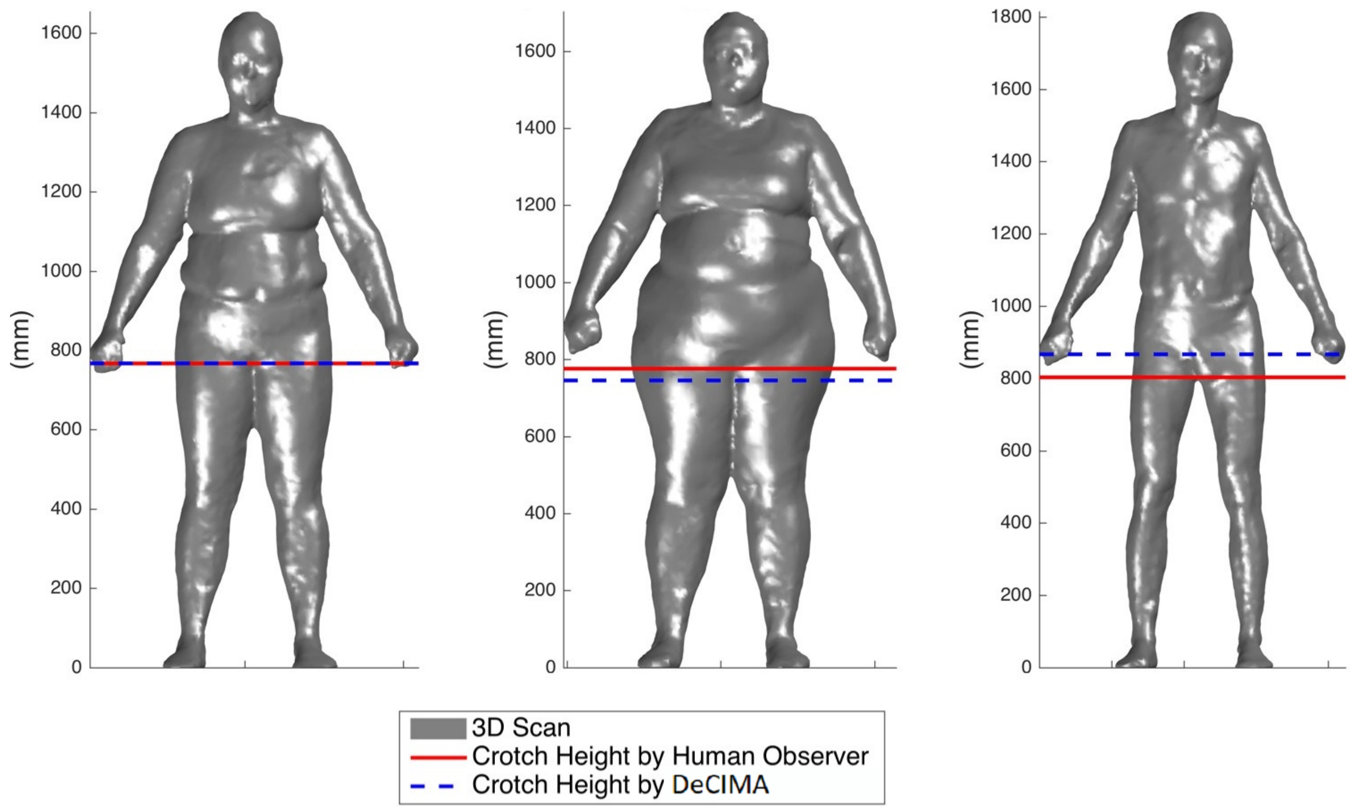

Figure 4. *3D scans indicating the crotch heights of human observer and DeCIMA, left: best estimate, middle: largest underestimate, right: largest overestimate.*

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Author Biography

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Peter Wolenski is the "Russel B. Long" Professor of Mathematics at Louisiana State University. His main research interests are optimal control theory and variational analysis.

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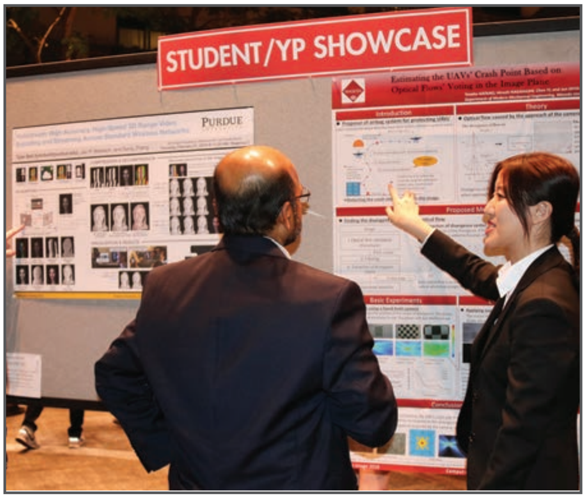

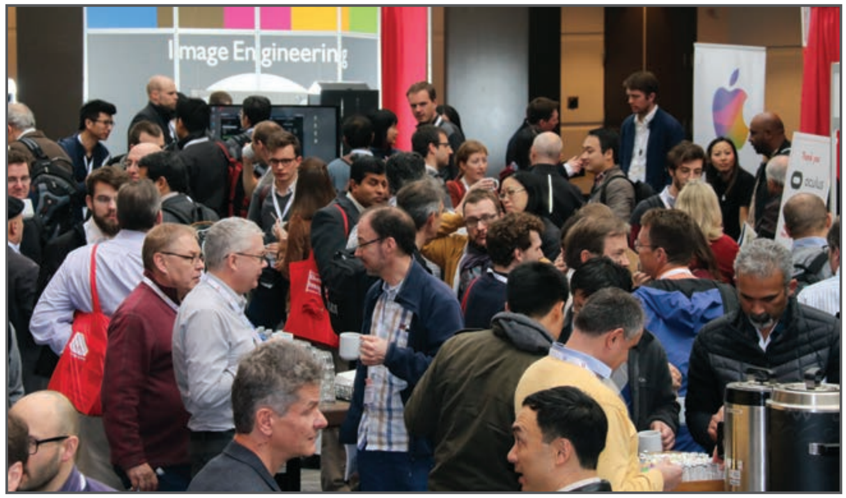

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