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Precision of the CAESAR scan-extracted measurements

Kathleen M. Robinette

Air Force Research Laboratory

Hein A.M. Daanen

TNO Human Factors
PO Box 23
3769 ZG Soesterberg
The Netherlands

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2800 Q Street, Bldg 824
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Kathleen M. Robinette (AFRL/HEPA)
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Precision of the CAESAR scan-extracted measurements

Kathleen M. Robinette[a,*], Hein A.M. Daanen[b]

[a]Air Force Research Laboratory, 2800 Q Street, Bldg 824, Wright–Patterson AFB, OH 45433-7947, USA
[b]TNO Human Factors, PO Box 23, 3769 ZG Soesterberg, The Netherlands

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Abstract

Three-dimensional (3D) body scanners are increasingly used to derive 1D body dimensions from 3D whole body scans for instance, as input for clothing grading systems to make made-to-measure clothing or for width and depth dimensions of a seated workstation. In this study, the precision of the scanner-derived 1D dimensions from the CAESAR survey, a multinational anthropometric survey, was investigated. Two combinations of scanning teams with 3D whole body scanners were compared, one called the US Team and the other the Dutch Team. Twenty subjects were measured three times by one scanner and one team, and three times by the other combination. The subjects were marked prior to scanning using small dots, and the linear distances between the dots were calculated after processing the scans. The mean absolute difference (MAD) of the repetitions was calculated and this was compared to reported acceptable errors in manual measurements from the US Army's ANSUR survey when similar measurements were available. In addition, the coefficient of variation (CV) was calculated for all measurements. The results indicate that the CAESAR scan-extracted measurements are highly reproducible; for most measures the MAD is less than 5 mm. In addition, more than 93% of the MAD values for CAESAR are significantly smaller than the ANSUR survey acceptable errors. Therefore, it is concluded that the type of scan-extracted measures used in CAESAR are as good as or better than comparable manual measurements. Scan-extracted measurements that do not use markers or are not straight-line distances are not represented here and additional studies would be needed to verify their precision.

Keywords: Anthropometry; Three-dimensional; Survey

1. Introduction

Although three-dimensional (3D) anthropometric scanners have a vast potential to capture the shape of human bodies, they are increasingly used to determine 1D body dimensions like stature and circumferences. 1D body dimensions like chest, waist or hip circumferences have been used for centuries and, as a result, there are many databases available such as the data collations by Jürgens et al. (1990), Coblentz et al. (1992) and Churchill et al. (1977). Over the centuries, designers have developed techniques for using 1D measurements, whereas they may not have developed methods to use the 3D information.

Coward et al. (1997) demonstrated that reference points which are recognizable from the surface contours can be reliably extracted by human observers from scan images. However, 1D dimensions often use palpation of the bony parts underneath the skin in order to identify reference locations. The waist circumference, for instance, should be measured as the circumference halfway between the tenth rib (bottom-most palpable rib) and the iliocristale (top of the iliac crest of the pelvis on the side) points, according to several standards. In most cases, such as in this example, these points cannot be determined by merely examining the surface, although some exploratory work has been performed in this area (Li et al., 2003; Suikerbuik et al., 2004). As a result, unless markers placed over palpated points can be effectively identified in the 3D scan, the resulting measurements can be very inaccurate.

In the Civilian American and European surface anthropometry resource (CAESAR) 3D anthropometric survey (Robinette et al., 2002; Blackwell et al., 2002; Daanen and Robinette, 2001), 72 landmarks were palpated and marked with stickers prior to scanning so that they could be

*Corresponding author. Tel.: +937 255 8810; fax: +937 255 8752.
E-mail addresses: kathleen.robinette@wpafb.af.mil (K.M. Robinette), daanen@tm.tno.nl (H.A.M. Daanen).

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visualized and extracted from the scan images. Then, 1D measurements consisting of distances between the landmarks or between the landmarks and standing or seated surfaces were calculated. Since there is no consensus yet on how to calculate circumferences from 3D scans unambiguously, all circumferences were taken in the traditional manner in CAESAR, rather than being extracted from scans. Therefore, circumferences are not examined in this study. This paper examines the relative precision of this method of extracting 1D measurements as compared against published precision measurements of traditional 1D measurements from the ANSUR study (Gordon et al., 1989).

ANSUR uses the term mean absolute differences (MAD) to indicate the error between repeated measures of the same subjects. These values were used to derive a maximum allowable error for measurement in that survey. Team members were then trained and monitored to stay within this level of error. The purpose of this study was to identify if these allowed differences for manual measurement were realistic and achievable with the 3D scan method.

Table 1
Statistics of the subjects

Subject	Gender	Age	Weight (kg)	Stature (cm)
1	M	25	58	170
2	F	18	64	165
3	M	21	70	186
4	F	27	85	178
5	M	23	61	179
6	M	19	111	192
7	M	21	80	183
8	M	22	78	188
9	F	20	67	178
10	M	20	76	193
11	F	23	63	182
12	F	21	51	167
13	F	18	76	177
14	F	26	72	181
15	M	26	64	175
16	F	21	61	169
17	F	20	66	168
18	M	19	80	168
19	M	23	107	199
20	F	18	85	168
Mean ± SD	M	22 ± 2	79 ± 18	183 ± 10
Mean ± SD	F	21 ± 3	69 ± 11	173 ± 7

2. Methods

2.1. Data collection

The measurements taken in this study were identical to the methodology used in the CAESAR survey. In the

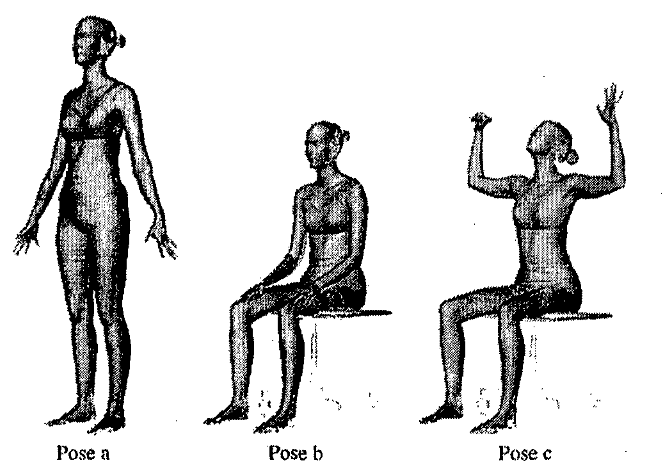

Fig. 2. Three CAESAR scan poses.

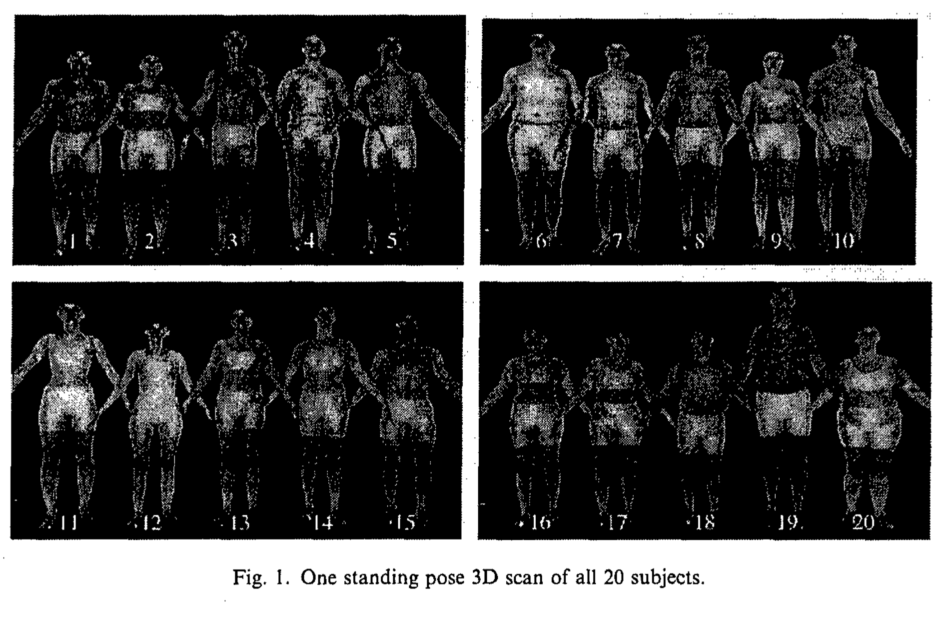

Fig. 1. One standing pose 3D scan of all 20 subjects.

CAESAR survey, about 5000 subjects were manually measured and scanned in Italy, The Netherlands and the US. At the end of the project, the Cyberware WB4 scanner (www.cyberware.com), used in the US and Italy, was shipped to the Netherlands and compared to the Vitronic Viro 3D Pro scanner (www.vitronic.de), used for the Dutch survey. Here, ten healthy male and ten healthy female subjects were pre-marked once, then 3D scanned six times, three times by the US Team and the Cyberware WB4 scanner and three times by the Dutch Team and the Vitronic Viro scanner. The scanners were in neighboring rooms, and two subjects were run at a time, one in one scanner and one in the other. After each scan, the subjects moved to the other scanner and team.

The subjects were selected in such a way that considerable variation in weight and stature existed. Some summary data of the subjects is shown in Table 1, and a picture of them in one of their standing pose scans is shown in Fig. 1.

Before scanning, markers were placed on 72 locations of the body. The landmark stickers appear as white circles on the body, as can be seen in Fig. 1. The subjects were scanned in three positions: a standing position and two seated positions, one with the hands on the thighs, and one

Table 2
Standing pose MAD results

Standing measures	Allowable error ANSUR (mm)	MAD US (mm)	SE mean US (mm)	MAD NL (mm)	SE mean NL (mm)
Acromial height, standing, left	7	4.8*	0.76	6.1	0.86
Acromial height, standing, right	7	3.9*	0.52	5.4	0.97
Acromion-radiale length, left	4	2.7*	0.37	4.0	0.49
Acromion-radiale length, right	4	3.2*	0.35	4.8	0.88
Arm inseam, left		2.4	0.35	3.9	0.40
Arm inseam, right		4.6	0.53	3.8	0.48
Axilla height, left	10	4.3*	0.58	5.7*	0.63
Axilla height, right	10	3.7*	0.49	5.3*	0.80
Biacromial breadth	8	5.0*	0.83	6.0*	0.78
Bi-cristale breadth		2.4	0.34	3.7	0.45
Bi-spinous breadth	3	2.1*	0.30	2.8	0.37
Bigonial breadth		2.4	0.38	3.0	0.66
Bitragion breadth		1.9	0.62	1.2	0.13
Bi-trochanteric breadth, standing		3.0	0.38	2.9	0.30
Bustpoint–bustpoint breadth	10	2.4*	0.37	3.0*	0.36
Cervicale height	7	2.4*	0.34	2.9*	0.32
Chest height	11	4.5*	0.49	4.7*	0.65
Elbow height, standing, left		5.2	0.99	6.8	0.69
Elbow height, standing, right		6.9	1.04	7.3	0.91
Foot breadth, left		2.0	0.30	3.5	0.61
Foot breadth, right	2	1.8	0.33	3.6	1.01
Infraorbitale height, standing, left		6.1	0.95	9.7	1.25
Infraorbitale height, standing, right		5.6	0.86	9.3	1.21
Interpupillary distance	2	2.6	0.34	3.1**	0.34
Interscye distance	10	8.0	1.83	7.9	1.36
Knee height, standing, left	6	1.5*	0.34	2.0*	0.28
Knee height, standing, right	6	1.5*	0.21	3.4*	0.42
Malleolus height, lateral, left	3	1.0*	0.18	2.6	0.48
Malleolus height, lateral, right	3	0.7*	0.11	1.3*	0.16
Malleolus height, medial, left		1.4	0.23	1.5	0.19
Malleolus height, medial, right		1.5	0.20	2.0	0.35
Neck height		5.1	0.77	7.7	1.23
Radiale-stylion length, left	6	3.0*	0.41	4.1*	0.47
Radiale-stylion length, right	6	3.4*	0.42	5.2	0.90
Sellion-supramenton length		2.2	0.25	3.1	0.42
Sleeve outseam length, left	6	3.3*	0.28	4.1*	0.55
Sleeve outseam length, right	6	3.1*	0.34	4.8*	0.58
Sphyrion height, left		1.4	0.15	1.9	0.19
Sphyrion height, right		1.2	0.28	1.9	0.31
Suprasternale height	5	3.7*	0.40	4.4	0.68
Trochanter height, left	7	3.0*	0.53	4.7*	1.05
Trochanter height, right	7	3.8*	0.94	4.3*	0.64
Waist back (cervicale to waist) length	5	3.4*	0.61	4.1	0.55

*Significantly better.
**Significantly worse.

with the hands up. These poses are shown in Fig. 2, and are referred to as poses a, b and c, respectively. For calculation of the scan-extracted measurements in CAESAR, only poses a and b were used.

The scans were processed and the *x*, *y* and *z* coordinates of the markers were determined semi-automatically using the software tool INTEGRATE (Burnsides et al., 2000). This involved having an operator view the color files in 2D and click in the middle of all markers. Then, the color file was mapped to the range data automatically with the calibration matrix and the points underlying the clicked locations were extracted and identified. This process and its effectiveness are described by Burnsides et al. (2001). All of the scan-extracted measurements were then calculated as Euclidean distances between points or points and planes defined by the points.

At the start of the CAESAR survey, both teams trained together to minimize the differences between the results. The Dutch measurement team conducted the Dutch CAESAR data collection about 2 years prior to this study and, therefore, may have lost part of their skills. The US measurement team consisted of two specialists, who conducted the American and Italian portions of CAESAR just prior to this study, finishing just 1 week prior. Therefore, the US Team was well practiced.

2.2. Data processing

The absolute value of the differences between repetitions for each subject was calculated for each dimension. The MAD and the standard errors of the differences were also calculated. MAD values provide a measure of precision, or consistency, of the measurement.

The ANSUR allowable errors were derived from MAD values from a similar repeated measures study. The CAESAR MAD values were compared with the ANSUR allowable errors when there was a similar measurement. Of the 43 standing measurements, 17 (51%) did not have a similar ANSUR measurement. Of the 16 seated measurements, 9 (56%) did not have an ANSUR counterpart.

This method of comparing precision is different than that used in studies by Bradtmiller and Gross (1999), McKinnon and Istook (2001), Paquette et al. (2000) and Saxton and Patterson (2000). In those studies, the absolute differences between manual and scan-derived measures were processed. The goal of the present study is to determine the comparative measurement repeatability, rather than the difference in the measurements.

Two tests of significance were performed. First a Sign Test comparing the CAESAR MAD scores to the ANSUR allowable errors was done to indicate an overall comparability. We hypothesize that the CAESAR MAD values and the ANSUR allowable errors for comparable measurements do not differ since, in both cases, the measurers were well trained. The two-sided alternative hypothesis is used. Next to the overall comparison of CAESAR to ANSUR allowable error, the individual measures were also compared to indicate which measures were more error prone.

Another commonly used measure of precision is the coefficient of variation (CV), which is the square root of

Table 3
Sitting pose MAD results

Sitting measures	Allowable error ANSUR	MAD US	SE mean US	MAD NL	SE mean NL
Acromial height, sitting (comfortable), left	9	5.2*	0.66	8.1	1.44
Acromial height, sitting (comfortable), right	9	5.4*	0.73	6.2*	1.24
Bi-lateral femoral epicondyle breadth, sitting (comfortable)		16.6	3.10	17.4	2.85
Bi-lateral humeral epicondyle breadth, sitting (comfortable)	17	9.2*	1.45	11.2*	2.37
Bi-trochanteric breadth, sitting (comfortable)		2.5	0.40	3.3	0.47
Buttock to trochanter length (comfortable)		2.7	0.38	5.6	0.99
Elbow height, sitting (comfortable), left	10	5.4*	0.91	7.7	1.51
Elbow height, sitting (comfortable), right	10	6.2*	0.81	5.8	1.24
Femoral epicondyle, lateral, left to malleolus, lateral (comfortable), left		2.6	0.44	3.2	0.70
Femoral epicondyle, lateral, right to malleolus, lateral (comfortable), right		2.6	0.49	4.9	1.14
Infraorbitale height, sitting (comfortable), left	8	5.4*	1.03	7.3	0.85
Infraorbitale height, sitting (comfortable), right	8	5.9*	0.95	7.6	0.98
Trochanter to femoral epicondyle, lateral (comfortable), left		4.4	0.54	7.8	2.31
Trochanter to femoral epicondyle, lateral (comfortable), right		3.9	0.53	6.9	0.89
Trochanter to seated surface comfortable, left		2.5	0.42	6.0	1.38
Trochanter to seated surface comfortable, right		3.4	0.75	4.7	0.71

All values in mm.
*Significantly better than ANSUR allowable error.
**Significantly worse than ANSUR allowable error.

the variance divided by the mean. The variance is calculated between three measures and averaged over subjects. This too was calculated and expressed as a percentage of the mean value (in other words, multiplied by 100).

3. Results

The results for the MAD values are shown in Table 2 for the standing posture and in Table 3 for the seated posture. The CV results are shown in Table 4 for the standing posture and in Table 5 for the seated posture. In these tables SE = standard error, NL = the Dutch Team, US = the US Team.

A Sign Test of the differences between MADs and allowable errors indicates that both the US and the Dutch Teams performed significantly better than the ANSUR allowable errors at $\alpha = 0.01$. For the US Team, 32 out of 33 differences were better and, for the Dutch Team, 29 of 32 differences were better (there was one tie).

All of the standing pose CAESAR MAD values were less than 10 mm. 82% of the US Team and 64% of the Dutch Team standing pose MAD values were less than 5 mm. Of the 33 measurements for which there was a suitable ANSUR allowable error, 30 (91%) of the US/Italy team MADs were significantly better than the allowable error, and the remaining 3 (9%) were not significantly different. The Dutch Team had 16 (48.5%) MADs that were significantly better than the allowable error, 16 (48.5%)

Table 4
Coefficients of variation (CV) for standing pose measurements

Standing measures	Mean US (mm)	Variance US	CV US (%)	Mean NL (mm)	Variance NL	CV NL (%)
Acromial height, standing, left	1471.7	20.1	0.3	1463.9	31.2	0.4
Acromial height, standing, right	1464.4	12.5	0.2	1451.9	28.6	0.4
Acromion-radiale length, left	337.9	6.2	0.7	334.3	12.8	1.1
Acromion-radiale length, right	334.1	7.4	0.8	333.1	24.6	1.5
Arm inseam, left	461.5	4.8	0.5	460.3	11.1	0.7
Arm inseam, right	458.5	16.3	0.9	459.1	12.5	0.8
Axilla height, left	1345.2	14.8	0.3	1341.8	24.4	0.4
Axilla height, right	1337.9	11.1	0.3	1325.5	24.2	0.4
Biacromial breadth	382.7	23.7	1.3	376.9	28.9	1.4
Bi-cristale breadth	314.0	4.8	0.7	308.9	9.6	1.0
Bi-spinous breadth	242.5	3.9	0.8	238.1	6.6	1.1
Bigonial breadth	111.6	5.4	2.1	114.8	10.1	2.8
Bitragion breadth	144.7	7.3	1.9	145.7	1.2	0.7
Bi-trochanteric breadth, standing	369.3	6.6	0.7	361.6	5.8	0.7
Bustpoint–bustpoint breadth	203.9	5.1	1.1	200.1	7.2	1.3
Cervicale height	1527.9	4.9	0.2	1520.1	6.8	0.2
Chest height	1302.6	15.7	0.3	1289.1	17.8	0.3
Elbow height, standing, left	1144.7	28.1	0.5	1143.9	33.5	0.5
Elbow height, standing, right	1143.4	44.6	0.6	1146.6	42.1	0.6
Foot breadth, left	98.5	3.7	2.0	99.4	17.3	4.2
Foot breadth, right	103.6	3.7	1.9	99.5	16.5	4.1
Infraorbitale height, standing, left	1646.4	32.3	0.4	1639.3	78.4	0.5
Infraorbitale height, standing, right	1646.6	27.5	0.3	1636.0	74.1	0.5
Interpupillary distance	68.2	5.5	3.4	66.0	7.3	4.1
Interscye distance	368.6	76.8	2.4	362.0	58.8	2.1
Knee height, standing, left	488.1	2.7	0.3	485.3	3.4	0.4
Knee height, standing, right	489.2	1.9	0.3	489.9	9.6	0.6
Malleolus height, lateral, left	71.2	1.0	1.4	71.2	7.0	3.7
Malleolus height, lateral, right	68.8	0.5	1.0	65.7	1.4	1.8
Malleolus height, medial, left	80.5	2.0	1.8	77.3	1.8	1.7
Malleolus height, medial, right	83.1	1.9	1.7	81.8	4.2	2.5
Neck height	108.8	22.6	4.4	108.0	52.1	6.7
Radiale-stylion length, left	258.6	7.3	1.0	255.8	13.4	1.4
Radiale-stylion length, right	264.4	8.8	1.1	266.0	27.8	2.0
Sellion-supramenton length	96.7	3.8	2.0	97.3	8.5	3.0
Sleeve outseam length, left	584.7	7.7	0.5	578.6	13.6	0.6
Sleeve outseam length, right	577.1	7.5	0.5	578.8	16.5	0.7
Sphyrion height, left	58.0	1.6	2.2	54.4	2.5	2.9
Sphyrion height, right	59.1	2.0	2.4	59.4	3.2	3.0
Suprasternale height	1449.6	10.9	0.2	1439.7	16.8	0.3
Trochanter height, left	970.4	9.1	0.3	968.3	25.3	0.5
Trochanter height, right	961.9	12.6	0.4	960.0	16.5	0.4
Waist back (cervicale to waist) length	451.2	11.4	0.8	446.6	14.5	0.9

Table 5
CV for sitting pose measurements

Sitting measures	Mean US (mm)	Variance US	CV US (%)	Mean NL (mm)	Variance NL	CV NL (%)
Acromial height, sitting (comfortable), left	607.0	19.8	0.7	602.6	65.1	1.3
Acromial height, sitting (comfortable), right	599.0	25.4	0.8	597.9	43.6	1.1
Bi-lateral femoral epicondyle breadth, sitting (comfortable)	398.0	290.8	4.3	389.1	273.0	4.3
Bi-lateral humeral epicondyle breadth, sitting (comfortable)	502.6	75.8	1.7	500.3	141.3	2.4
Bi-trochanteric breadth, sitting (comfortable)	374.5	5.7	0.6	367.5	9.9	0.9
Buttock to trochanter length (comfortable)	198.0	7.0	1.3	202.6	30.8	2.7
Elbow height, sitting (comfortable), left	283.0	26.9	1.8	280.4	57.1	2.7
Elbow height, sitting (comfortable), right	276.8	34.4	2.1	280.3	40.8	2.3
Femoral epicondyle, lateral, left to malleolus, lateral (comfortable), left	415.2	5.3	0.6	405.8	12.0	0.9
Femoral epicondyle, lateral, right to malleolus, lateral (comfortable), right	407.6	7.8	0.7	400.3	31.0	1.4
Infraorbitale height, sitting (comfortable), left	784.0	30.9	0.7	784.2	43.4	0.8
Infraorbitale height, sitting (comfortable), right	784.1	32.7	0.7	785.0	48.9	0.9
Trochanter to femoral epicondyle, lateral (comfortable), left	454.6	15.1	0.9	452.0	96.4	2.2
Trochanter to femoral epicondyle, lateral (comfortable), right	450.9	13.0	0.8	444.0	40.6	1.4
Trochanter to seated surface comfortable, left	160.2	6.3	1.6	155.0	44.2	4.3
Trochanter to seated surface comfortable, right	154.8	15.4	2.5	159.8	16.8	2.6

that were not significantly different from the allowable error and one (3%) that was significantly worse. All but one of the CV values were less than 5%, and anything below 5% is considered to be very good. The only one that was greater than 5%, neck height for the Dutch Team, was 6.68%.

4. Discussion and conclusion

Three-dimensional imaging provides a copy of the subject that can be continually re-interrogated to extract new measurements long after the subject is gone, whereas manual measurement has very limited capability to construct new measurements. However, there has been a concern that measurements extracted from the images may not be as precise. This study refutes that concern and indicates that CAESAR scan-extracted linear measures are more accurate than the traditional measuring reflected in the ANSUR survey allowable errors. The CAESAR scan-extracted measurements appear to be extremely accurate, regardless of the team or scanner used. A majority of the MADs were less than 5 mm, and only one CV was greater than 5%. The US Team with the Cyberware scanner was particularly good, with MAD scores overwhelmingly better than the ANSUR allowable error. The fact that they were well practiced, having just completed the Italian portion of the CAESAR project, may have contributed to their precision. The Dutch Team that was 2 years out of practice had larger MAD scores than the US Team but still was significantly better than the ANSUR allowable errors. In some instances the improvement was pronounced. For example, the allowable error for bustpoint–bustpoint breadth was 10 mm, but the MADs were just 2.4 and 3.0 mm for the US and Dutch Teams, respectively.

It must be noted that the CAESAR scan-extracted measurements were all height and point-to-point distance measurements from pre-marked landmarks. No circumferences or arcs that follow surface contours were included. All circumferences and arcs were taken in the traditional manner in CAESAR, rather than being extracted from scans. Previous studies indicate that circumferences and arcs are much more difficult to obtain reliably from scans. Perkins et al. (2000) examined three ways to calculate the same measurement from a scan with landmarks. One followed the surface contour partially, one followed the contour fully and one was a point-to-point straight-line distance. The two methods that followed the contours had more measuring error and less reproducibility than the straight-line distance. The measure that followed the contour completely had a standard deviation that was twice that of the straight-line distance. Therefore, additional research must be done to examine the reliability of circumferences and arcs.

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