Extraction of Encumbered Anthropometric Measures from Whole-Body Scan Data

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Accurate capture of encumbered anthropometry is critical to ensure that the analysis and design of military platforms and workspaces account for the additional space required for clothing and PPE equipment. To examine the effect of encumbrance on spatial claim, a method was developed to obtain scan-extracted measures from detailed whole-body shape data. This analysis focused on comparing cross-sectional measures extracted from 3D scan data with measurements of the same participants obtained by traditional 1D techniques, while donning different levels of clothing and equipment.

INTRODUCTION

The Canadian Armed Forces (CAF) utilizes semi-nude anthropometric data for the analysis and design of military clothing, equipment, platforms and workspaces. These measurements are critical for investigating key human factors criterion such as performance, safety, and crew station accommodation. While ISO standards such as ISO-7250-1 detail how to take anthropometric measurements of individuals who are semi-nude, there is little guidance in the literature on how to account for the effect of encumbrance on body shape and spatial claim. MIL- STD-1472G cites that because anthropometric data represent nude body measurements, "suitable adjustments (~provide clothing or equipment delta factors) in design-critical dimensions shall be made for light or heavy clothing, flying suits, helmets, boots, body armour, load-carrying equipment, protective equipment, hydration packs, and other worn or carried items". This presents scant objective guidelines as to how much additional space is to be allowed for clothing and equipment or how to determine the spatial claim of an individual.
A small number of published studies have investigated encumbered anthropometry measurements (Carrier and Meunier, 1996; Paquette et al., 1999; Guitierrez & Gallagher, 2008). Paquette et al. (1999) proposed that the height of an anatomical landmark would not change between semi-nude and encumbered conditions. Based upon this premise, Jones et al. (2013) has proposed two landmark paradigms, Normalized to Anthropometry and Maximal Bulk. Specifically, the Normalized to Anthropometry paradigm involves acquiring breadth, depth and circumferential measures at cross-sectional heights associated with anatomical landmarks. The effect of encumbrance on spatial claim, termed as bulk, is quantified by comparing clothed and semi-nude measurements at each respective landmark height.

Accuracy and variability of three-dimensional (3D) body scan extracted measurements compared with traditional-derived anthropometric measures has been examined (Bradtmiller and Gross, 1999; Paquette et al., 2000; Qi et al., 2011). Sources of error that contribute to the difference between 3D body scan and manually derived body dimensions include, but are not limited to: 1) repeatability of landmarking and measuring, including compression of tissue, hair or clothing, 2) quality of the 3D scan, presence of occlusions or voids, 3) consistency in definition (anatomical and algorithmic) of traditional and scan-extracted measures, and 4) posture and postural sway during quiet stance and continuous movement produced by breathing and involuntary muscle reflexes during scanning and traditional measurement. An international standard exists to standardize the protocol to evaluate the comparability of body dimensions obtained by traditional methods and 3D scanning (ISO 20685: 2010 (E)). To date, the research and development of 3D scan extraction protocols have focused on measurements obtained from participants in semi-nude or minimally clad clothing conditions. There is little data in the literature to indicate the extent to which these results apply to the accuracy and precision of 3D scan-derived encumbered anthropometric measures.

The current research is part of a larger effort to develop a standard encumbered anthropometric protocol that produces accurate and repeatable metrics for bulk. The objective of the current analysis is to evaluate the efficacy of customized algorithms (Human Solutions® Anthroscan) developed to extract one-dimensional (1D) measurement from 3D scan data. 1D measurements include breadth, depth, and circumference of the participant taken at specified heights. It is hypothesized that 3D extraction techniques can provide a reasonable estimate of the effects of encumbrance on a participant's spatial claim and accurately reflect traditionally-derived measures.

METHODS

Participants

Data were gathered from twenty-two military male and five female volunteers. The male study population averaged 1.76 m for stature, 79.9 kg for weight, and 29.4 kg/m^2 for body mass index (BMI). Female participants averaged 1.70 m for stature, 84.6 kg for weight, and 29.4 kg/m^2 for BMI. DRDC Toronto's Human Research Ethics Committee (HREC) approved the research protocol.

Anthropometric Measures

Four cross-sectional reference heights were nominally chosen at four anatomical landmarks. Cross-sectional measures were

acquired at the horizontal slice defined at the following landmarks: 1) acromion, 2) deltoid point, 3) chest, and 4) waist (omphalion) (Figure 1). Reference heights were established under semi-nude conditions and used to parameterize the cross-sectional breadth, depth and circumferential measures during traditional 1D measures of both semi-nude and encumbered clothing conditions (Jones et al., 2013).
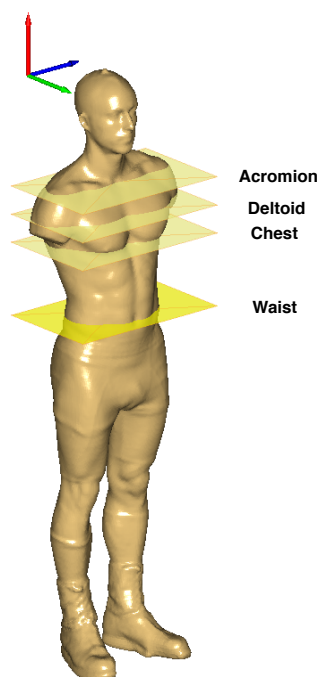

Figure 1. Illustration of the Normalized to Anthropometry paradigm. Highlights the reference height associated with the anatomical landmarks for the Normalized paradigm (Jones et al., 2013)

3D Scan Measures

A VITUS XXL (Human Solutions of North America, Cary, NC) scanner was used to capture whole-body 3D data. Participants were scanned twice, first with arms at sides (Posture 1), and second with arms raised approximately 30° (Posture 2) to ensure that the extremities were abducted from the torso for scanning clearance between the extremities and the torso/clothing; caution was taken in Posture 2 to minimize alterations in torso measurements. Scan-extracted measures including arms, defined by the acromion and deltoid heights, were obtained from Posture 1 scans, and those measures excluding arms, defined at the level of the chest and waist, were extracted from Posture 2 scans (Figure 2). Reference heights derived during the traditional 1D measures were applied as reference inputs to the scan extraction algorithm. Horizontal cross-section slices were extracted from the 3D body scan at each reference height to compute breadth, depth, and circumferential measures.

Test Conditions

Participants donned three levels of encumbrance while being measured by both traditional 1D anthropometric and 3D

scanning methods. The test conditions included an unencumbered (semi-nude) and two encumbered configurations for each participant, as outlined in Table 1 below. Semi-nude was defined as compression shorts and sports bra only. Tactical vests and fragmentation vest were sized according to the participant's body dimensions. Clothing straps and components were adjusted in an attempt to standardize fit across the participants. For each test condition, measurements were acquired both by traditional 1D methods, and 3D scan measurement extraction. Test condition order was randomized across participants.

Table 1. Three load conditions were evaluated in this study: one unencumbered (semi-nude) and two encumbered conditions (E1 & E2). The load conditions were comprised of in-service Canadian Army personal protection equipment (PPE) for dismounted combat soldiers.

Condition	Level of Encumbrance
UE	Unencumbered (semi-nude; compression shorts & bra)
E1	Combat fatigues, Tactical Vest with PPE
E2	Condition E1 + Fragmentation Vest & Plates (front and back hard body armour)

Prior to testing, participants were asked to assume a natural, comfortable standing posture. To ensure a consistent posture, participant's preferred foot placement was recorded on a scaled grid. Participants were instructed to maintain their foot posture throughout the measurement and scanning of all clothing conditions. Participants were landmarked on their right side to identify reference heights associated with the acromion, deltoid, chest, and waist (omphalion). Three self-leveling laser levels were used to provide precise reference to the cross-sectional heights during the traditional measurement. Maximal measurements were acquired at each horizontal slice: breadth in the frontal plane, depth in the sagittal plane, and circumference as a convex measure about the PPE (does not follow contour of body exactly). Breadth and depth measurements used beam calipers with lasers aligned across all sides to ensure minimal torque. Circumference measurements utilized the measuring tapes' 4oz tension indicator (Gulick II) to ensure constant tension. It also ensured that all manual measurements were taken without compressing the clothing to obtain maximal measurements.

3D Scan Post-Processing & Scan Extraction

Prior to measurement extraction, each 3D scan required post-processing in the Human Solutions software environment. A triangular mesh surface reconstruction algorithm to fill voids, entitled "Human Texture" was applied to each of the scans (ScanWorX Version 2.9). The automatic algorithm was applied with no manual correction of landmark positioning. Additionally, Posture 2 scans were manually modified such that the participant's arms were removed prior to the application of the mesh (Figure 2).
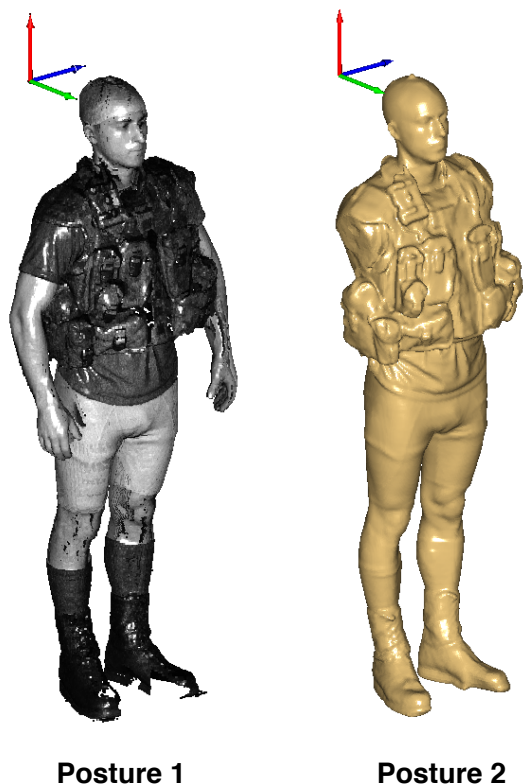
Posture 1   **Posture 2**

Figure 2. Body scans in the two postures for one participant.   Posture 1 is an example of a raw scan and Posture 2 of a reconstructed scan.

Customized code was developed within the Human Solutions software environment (Anthroscan Version 3.0.5) to extract breadth, depth, and circumference measurements from each cross-sectional reference height.   Linear breadths were defined as the projected distance between the left most prominent point and right most prominent point along a direction vector perpendicular to the facing direction of the participant (Figure 3).   Linear depths were extracted as the projected distance between the front most prominent point and back most prominent point along a direction vector parallel to the facing direction of the participant (Figure 3). Both linear measures employed a function that returned the projected distance measure between two points (p1 and p2) along a vector (d).
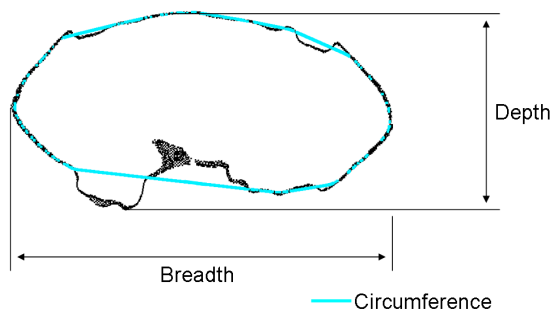

Figure 3. Representative cross–section illustrating the scan-extracted measures for an individual reference height.

Circumferential measures were computed using the "Take Closed Tape Measure" function, which calculated a circumference around adjacent points in a 3D plane (Figure 3). This function is predicated on an assumption of contiguous geometry defined in the plane parallel to the floor. A nearest neighbor distance algorithm (value of 0.02 mm) was used to ensure that the set of points in the plane are adjacent geometry to the nearest point in the plane. The intent of this function was to compute a tape around the geometry within a 2D horizontal slice that was extracted at a prescribed reference height.

Data Analysis

The performance of the scan-derived measurements was evaluated in terms of accuracy. For each anthropometric measure, the mean absolute difference (MAD) was computed to report the measurement difference between the traditional (m_{1D}) and scan-extracted (m_{3D}) measures across the clothing conditions (ISO 20685: 2010 (E)). The MAD was calculated by taking the absolute value of each of the individual differences, and then taking the mean of those absolute value differences.

$$MAD = \frac{\sum |m_{1D} - m_{3D}|}{n}$$

For the purpose of accuracy evaluation, an analysis of variance was used to evaluate the MAD values. The null hypothesis proposed that the mean difference between the two measurements is zero. Post-hoc Tukey tests were then performed on significant main effects of load condition. An alpha level of 0.05 was adopted for all pairwise comparisons.

To exclude abnormal data from the analysis, differences between a scan-extracted and traditional measure that deviated from the range of "the mean difference $\pm 3\ \sigma$" (σ: SD of differences) were considered abnormal and excluded from the analysis. The abnormal difference values were generally a result of recording errors and 3D body scan measurement errors due to poor quality of scan data.

RESULTS

Table 2 summarizes the evaluation results of the accuracy of the scan-derived measurements. The pairwise comparison results indicate that a significant difference was found between the scan-extracted and traditional 1D measurements in 6 of the 11 anthropometric measures (Table 2). MAD values of most of the linear depth dimensions, select breadth measures, and one circumferential measure were less than 10 mm. In comparison, most of the circumferential measures produced relatively larger MADs. To provide further context, MAD values were verified relative to the ISO 20685 criterion and none of the MADs observed in the study meet the maximum allowable differences.

Table 2. Evaluation results of accuracy across cross-sectional measure. PPE refers to clothing conditions: unencumbered (semi-nude) and two encumbered conditions (E1 & E2). MAD refers to mean absolute difference in centimeters between the scan-derived and traditional 1D measurement. * Significant difference between the two methods (p<0.05).

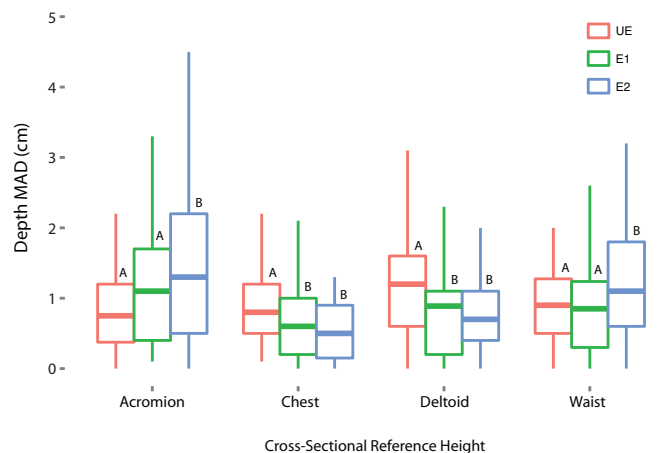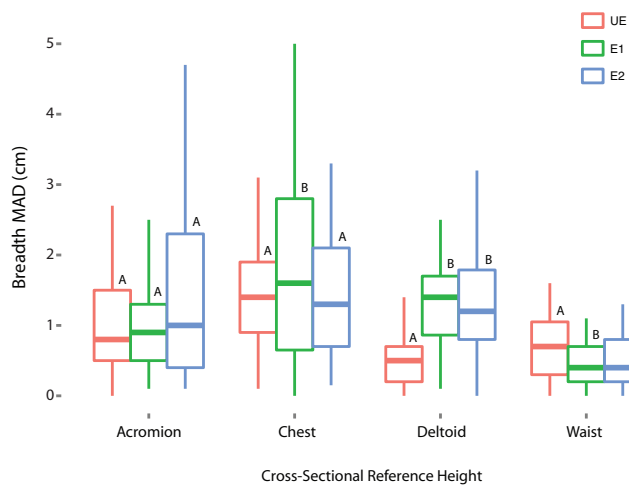| Cross-Section	PPE		Breadth MAD (cm)		Depth MAD (cm)		Circumference MAD (cm)
Acromion	UE		1.1 (1.0)		0.9 (0.6)		
	E1	NS	1.2 (1.1)	NS	1.2 (1.0)		
	E2		1.4 (1.2)		1.6 (1.3)		
Chest	UE		1.4 (0.8)		0.9 (0.6)		1.8 (1.4)
	E1	*	2.3 (2.0)	*	0.6 (0.5)	NS	2.0 (1.8)
	E2		1.8 (1.4)		0.6 (0.6)		1.5 (1.1)
Deltoid	UE		0.7 (1.0)		1.2 (0.7)		1.6 (2.7)
	E1	*	1.3 (0.6)	*	0.8 (0.7)	*	1.0 (1.2)
	E2		1.3 (0.8)		0.8 (0.5)		1.3 (1.0)
Waist	UE		0.7 (0.5)		0.9 (0.7)		0.9 (0.6)
	E1	NS	0.5 (0.3)	NS	1.1 (1.1)	*	2.4 (1.9)
	E2		0.5 (0.4)		1.3 (1.0)		3.8 (3.8)

Figure 4. Comparison of mean absolute differences (MAD) between traditional and 3D scan-extracted breadth (ISO Standard: 0.4 cm MAD) and depth (ISO Standard: 0.5 cm MAD) measures across clothing conditions. Cross-sectional reference heights indicated by different letters (i.e. A and B) are significantly different at alpha level of 0.05.
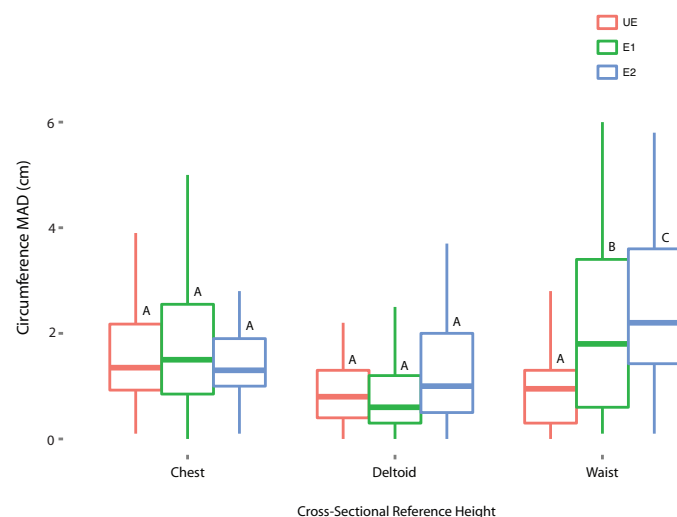

Figure 5. Comparison of mean absolute differences (MAD) between traditional and 3D scan-extracted circumferential (ISO Standard: 0.9 cm MAD) measures among clothing load conditions. Cross-sectional reference heights indicated by different letters (i.e. A and B) are significantly different at alpha level of 0.05.

No discernible trends were established for MADs across the clothing conditions (Figures 4 & 5). MAD values were found to both increase and decrease with levels of encumbrance across the cross-sectional measures. To interpret the relevance of these results, comparisons were made of the order of magnitude of MAD detected between the unencumbered and encumbered clothing conditions, for each anthropometric cross-sectional measure. Typically, the differences between MAD values observed between UE and E1or E2 load conditions ranged from 0.2 to 0.9 cm. The only exception was a 2.9 cm difference between the MAD that resulted from anthropometric measures acquired at the waist height for the UE and E2 levels of PPE.

DISCUSSION

To examine the effect of bulk on spatial claim, a method was developed to obtain scan-extracted measures from detailed encumbered body shape data. This analysis focused on comparing cross-sectional measures of encumbered anthropometry extracted from 3D scan data with measurements of the same participants obtained by traditional 1D techniques, while donning different levels of encumbrance or clothing. Clearly, it is shown that it is possible to obtain anthropometric data extracted from semi-nude and encumbered 3D body scans that are very close to traditionally measured values. To provide context MAD values were

compared against the MADs reported in two previous studies, as well as the ISO 20685 criteria. Both the unencumbered and encumbered MADs fell short of the benchmark differences for extracted dimensions set by the international ergonomics standards (ISO 20685). MAD is a strict measure of the difference between two methods and its utility with respect to scan extraction of encumbered anthropometry should be evaluated. However, the results of this study demonstrate better accuracy, with smaller MAD values, as compared to those reported by Bradtmiller and Gross (1999) and Qi et al. (2011). The level of accuracy obtained from this scan-extraction methodolgy, which was applied to 3D scan data of encumbered participants, did not differ in magnitude relative to MAD values derived from semi-nude 3D scan extraction (Qi et al., 2011). Linear measures were observed to be more accurate than circumferential, which is also a consistent trend with 3D scan extraction research based upon semi-nude participants (Perkins et al, 2000).

Challenges with encumbered anthropometric measures were highlighted by the significant difference in waist height circumferential MAD measures as a function of encumbered conditions (Figure 5). This is likely because the PPE equipment was bulkiest within this region. Among the unique sources of error that may contribute to the difference between 3D body scan and manually derived body dimensions for encumbered anthropometry include, but are not limited to: 1) clothing compression (variability between loose clothing and hard rigid PPE), 2) irregular surface geometry of clothing and rigid PPE equipment, 3) fit of the PPE equipment relative to the semi-nude anthropometry of a participant, 4) postural sway and inconsistencies may increase with increasing levels of PPE and body worn mass (~15 kg) , and 5) the ability to standardize the fit of PPE equipment given its adjustability given its movement with participant movement across measurement techniques.

REFERENCES

Bradtmiller, B. And Gross, M.E. (1999). 3D whole-body scans: Measurement extraction software validation. SAE Transactions, 108(1), 394-400.

Carrier, R. and Meunier,P. (1996). Effect of Protective equipment on anthropometric measurements and functional limitations. DCIEM Report No. 96-CR-22. Toronto, Canada: Department of National Defence.

Guitierrez, C. M., & Gallagher, P. D. (2008). Pilot Study of Firefighter Three-Dimensional Anthropometry to Improve Seatbelt Safety (pp. 144). Gaithersburg, MD 20899-8661: National Institute of Standards and Technology.

ISO. (2008). International Standard ISO 7250-1:2008(E): Basic human body measurements for technological design — Part 1: Body measurement definitions and landmarks. Geneve, Switzerland.

ISO. (2010). International Standard ISO 20685:2010(E): 3D scanning methodologies for internationally compatible anthropometric databases. Geneve, Switzerland.

Jones, M. L. H., Farrell, P. S. E., & Keefe, A. (2013). Encumbered Anthropometry Protocol Development. Proceedings of the 2013 International Ergonomics Society Digital Human Modeling Symposium. Ann Arbor, USA.

MIL-STD 1472G. 2012. Department of Defense Design Criteria Standard – Human Engineering. United States Department of Defense.

Paquette, S., Brantley, J.D., Corner, B.D., Li, P., and Oliver, T. (2000). Automated Extraction of Anthropometric Data from 3-D Images. Paper presented at the 2000 International Ergonomics Association, San Diego, USA.

Paquette, S. P., Case, H. W., Annis, J. F., Mayfield, T. L., Kristensen, S., and Mountjoy, D.N. (1999). The Effects of Multilayered Military Clothing Ensembles on Body Size: A Pilot Study. Technical Report NATICK /TR-99/012. United States Army Natick Research, Development and Engineering Center Natick, MA.

Perkins, T., Burnsides, D.B., Robinette, K.M., and Naishadham, D. (2000). Comparative consistency of univariate measures from traditional and 3-D scan anthropometry. In: Proceedings of the SAE International Digital Human Modeling for Design and Engineering International Conference and Exposition. Dearborn, Michigan, USA.

Qi, J., Zhang, X., Ying, B. and Lv, F. (2011). Comparison of Human Body Sizing Measurement Data By Using Manual and 3D Scanning Measuring Techniques. Journal of Bioengineering & Informatics. 4:1, 83-95.