**A Pilot Study of Three-Dimensional Equipped Anthropometry**

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Accurate capture of equipped 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 personal protective equipment (PPE) on spatial claim, methods were developed to model the effects of body armor and PPE relative to body size and shape. The new methods describe contour shape profiles that characterize meaningful size and shape variation of the torso with the addition of clothing and PPE ensembles. A pilot study was conducted with 15 military men.

**Practitioner Summary:** With these methods, detailed 3D clothed or equipped body shape data can be modeled. Data from a larger sample will be useful for improving the design and assessment of military vehicles and workspaces.

**Keywords:** anthropometry, body scan data, personal protective equipment, accommodation, design applications

1. **Introduction**

The design of military vehicles and workspaces are based primarily on dimensional guidelines that are directed by standard anthropometric dimensions (lengths, widths, circumferences). MIL-STD-1472G (Department of Defense, 2012) cites that because “anthropometric data represent nude body measurements, suitable adjustments in design-critical dimensions shall be made” for personal protective equipment (PPE). Notably, the current guidelines do not take into account the effects of body armor or PPE on operator anthropometry. The effects of PPE on spatial claim for soldiers are important for workspace design. A knowledge gap persists on how to parameterize the effect of soldier PPE on body shape and spatial claim.

A small number of published studies have investigated equipped anthropometry. However, there is significant disparity in the measurement of equipped anthropometry. Methodologies range from standard anthropometric measures (Carrier and Meunier, 1996; Guitierrez & Gallagher, 2008; Hsiao et al., 2014), dimensions recorded at prescribed heights defined by landmark paradigms (Paquette et al., 1999; Jones et al., 2013), and multivariate model-based methods (Reed and Ebert, 2013).

This paper describes a pilot study conducted of methods using standard anthropometry and three-dimensional body scans to develop the data needed to model the effects of body armor and PPE on body size and shape. The current analyses describe contour shape profiles that characterize meaningful size and shape variation of the torso segment with the addition of clothing and PPE ensembles.

2. **Methods**

The current methods were developed from those presented by Reed and Parkinson (2008). The scan data was mapped to a uniform representation to enable statistical representation of the equipped soldier.

Since torso shape is the most salient feature of whole body shape and the body segment most implicated while donning the PPE ensembles considered in this pilot study, the following method and implementations are on the torso shape only.

2.1 **Pilot Study Participants**

Fifteen military men participated in the pilot study. This pilot study sample was drawn from a larger pool of Canadian Armed Forces (CAF) infantry and combat engineer soldiers participating in the 2014 Load Effects Assessment Program. Table 1 lists the standard dimensions for the participants.
Table 1. Standard Anthropometry: Selected Dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stature (m)</td>
<td>1.69</td>
<td>1.78</td>
<td>1.89</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.9</td>
<td>88.2</td>
<td>99.0</td>
</tr>
<tr>
<td>BMI (kg/m^2)</td>
<td>23.3</td>
<td>27.7</td>
<td>31.8</td>
</tr>
</tbody>
</table>

2.2 Anthropometry

Standard anthropometric dimensions, including stature, body weight, and linear dimensions (lengths, widths, and circumferences) were recorded using procedures generally identical to those used in ANSUR (Gordon et al. 1989). A VITUS XXL (Human Solutions, LLC) whole-body laser scanner was used to capture whole-body 3D surface data at each level of PPE (Figure 1).

![Figure 1. A. Measuring biacromial breadth. B. Participant in the Vitus XXL whole-body laser scanner.](image)

2.3 Test Conditions

Participants donned four ensembles: minimally clad which consisted of fatigues only (UE), a vest with soft armor ballistic fills that was 20 mm in thickness (E1), a tactical vest equipped with full fighting order i.e., personal-protective equipment (E2) alone, and wearing the soft armor fill and PPE (E3) (Figure 2). Tactical vests and PPE were sized according to the participant’s body dimensions, as prescribed by the CAF. All adjustable components of the PPE (i.e. straps, belts, and buckles) were altered in an effort to standardize fit across the participants. Test condition order was randomized by ensemble level.
2.4 Protocol

Defence Research & Development Canada (DRDC)’s Human Research Ethics Committee (HREC) approved this research protocol.

During testing, participants were asked to assume a natural, comfortable standing posture (Figure 3). To minimize the effect of postural variability, participant’s preferred foot placement was recorded on a scaled grid. Participants were instructed to maintain their foot placement and posture throughout the measurement and scanning of each test condition.

Each participant was scanned in two standing postures for each test condition. Participants maintained their arms at the sides for the first posture, and raised or abducted their arms approximately 30° relative to vertical for the second posture. The objective of the second posture was to ensure that the areas of interest on the torso were not shadowed from the whole-body scanner. Caution was taken to minimize alterations of the fit of the PPE relative to the torso during arm abduction. All testing was completed in a single session lasting approximately one hour.

2.5 Scan Data Processing

The surface data obtained from the laser scanners were pre-processed in the ScanWorX software (Human Solutions, GmbH). First, artifacts (for example, platform and foot-grid) were manually removed. Scan postures with the arms of abducted were modified further, such that the participant’s arms were segmented from the torso (Figure 3). The segmentation of the point cloud between the upper arm and torso was completed manually. Researchers visually identified the gap and adjusted the segmentation plane to properly section the point cloud.

Segmentation of the torso and upper arm from the whole-body was derived from the two scan postures. An automated method was used to ensure that the segmentation is accurate. Algorithms based on
anatomical landmark locations were supplemented by a visual search process, in which researchers interactively adjusted the segmentation planes to properly section the point cloud.

### 2.6 Cylindrical Sampling

Data reduction processes involved the extraction of horizontal slices at 5-mm vertical intervals from the raw three-dimensional data (Figure 4). These vertical slices were normalized to a participant’s stature, specifically between the heights associated with C7 and hip joint centre of rotation (40 slices per scan). Data from each slice was sorted using a nearest neighbour technique and filtered such that the vertices create a continuous planar contour that interpolates across holes while preserving the real concavities in the surface contour.

Points within each individual slice were transformed from Cartesian to cylindrical coordinates. A radial point-sampling method was then applied in each slice to create an equal number of surface vertices at even radial increments. The result is that each participant’s torso data is represented by a uniform number of vertices (100 per cross-section). Origin of the cylindrical coordinates was located along the longitudinal torso axis (z-axis), which was constructed by projecting a vector from the cervicale to a centroid representing the pelvis landmarks. The resulting x-axis projects through the front of torso to define the sagittal plane, while the y-axis projects through the right torso side to define the coronal plane.

![Figure 4: Scan data represented in horizontal slices to create continuous contours (A) and transformed into cylindrical coordinate sampling scheme on the torso surface (B).](image)

### 2.7 Extraction of Contour Shape

To illustrate the effect of PPE ensembles on torso shape, 2D contour profiles (~silhouettes) offer simplified, representational rendering of size and shape. Radial-based sampling methods enabled contour shape descriptors to be extracted at equal angular space (the azimuth angle) and radial distances from the longitudinal torso axis to the point on the surface data (Figure 5). For this pilot study, silhouettes that parameterize the torso shape in the sagittal (yz) plane and coronal (xy) plane reference planes were extracted from the segmented torso for each test conditions.
Figure 5: Radial based sampling of each cross-sectional slice in the horizontal plane. Representative series of contours, at equal 10-degree angle spacing, characterized along the longitudinal torso axis.

2.8 Data Analysis

Statistical significance was tested using the means and 95th percentile bootstrap confidence intervals (Lam et al., 2002; Moore et al., 2003). This technique allows estimation of the empirical sampling distribution of the torso contour shapes in the sagittal and coronal planes by randomly re-sampling the original observations.

3. Preliminary Results

“Average” contour shape profiles of the torso segment and their variability represented by the width of the confidence intervals at a given normalized heights were quantified for each PPE ensemble test condition to determine the statistical significance of differences. Figure 6 illustrates the average contour shapes in the sagittal (yz) plane and coronal (xy) plane, with the longitudinal torso axis defined at zero. Group differences between PPE ensemble test conditions were more pronounced in the coronal compared to sagittal plane. Relative to the minimally clad (UE), the average median increase in contour shape for the E2 and E3 test conditions was approximately 125 mm to the right and 75 mm to the left in the coronal plane. Minimal differences were found between the soft armor only (E1) and soft armor and PPE (E3) conditions.
Figure 6: Contour shape profiles for each of the PPE ensembles: minimally clad (UE) - red, soft armor (E1) – grey, PPE (~tactical vest) only (E2) - blue, and soft armor + PPE (E3) – green. A. Sagittal (yz) plane. B. Coronal (xy) plane. Summary mean average denoted with a solid mean line. Confidence intervals denoted as grey lines that outline color bands for each test condition.

4. Discussion

This pilot study developed methods for obtaining and parameterizing detailed body shape for clothed or equipped operators. These methods demonstrate that 3D body contours or silhouettes enable the parameterization of PPE shape, relative to the underlying body shape, to provide an estimation of how the clothing ensembles influence human shape. Visualization of the effects of PPE ensembles on spatial claim relative to the minimally clad body shape highlights the importance of capturing 3D shape of equipped anthropometry.

The current analysis illustrates the sagittal and coronal body contours of the equipped soldier in a standardized posture only. One important concern is that contour measures extracted within the anatomical references planes do not necessary reflect the maximal clearance or spatial requirements for a clothing/PPE ensemble. For the purpose of design of military platforms and workspaces, it is imperative such measures accurately account for the maximal additional space required for clothing and PPE equipment.
Further analysis and methodological development will integrate both the geometric contour surfaces and standard anthropometric priors to construct statistical models of the equipped body shape. The framework and accuracy of this approach can be found in previous studies (Allen et al., 2003; Reed and Parkinson, 2008). Specifically, multivariate statistical methods will be performed on the cylindrical coordinate data and used for modeling body shape. Principal component analysis (PCA) will be used as a data reduction method. By linking the principal components with overall body dimensions and soldier attributes, such as PPE ensemble (UE, E1, E2, and E3), the developed model will predict equipped body shape and parametrically assess and compare the corresponding space claims.

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References