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Anthropometric Manikins for the Design and Evaluation of Soldier Equipment

Alistair Furnell

Land Division
Defence Science and Technology Group

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ABSTRACT

Currently soldier systems engineers often use a typical tailor's dummy to design and evaluate torso borne Soldier Combat Ensemble (SCE) items like harnesses and chest rigs. It is not known how the dummy's size and shape was established, but it is likely not based on current Australian Army anthropometric data. This report contains details of the use of the Principal Components Analysis method to select a representative selection of body scans from the Australian Army Anthropometric survey and manufacture them into physical manikins. The aim is to provide design tools based on real Australian Defence Force member's size and shape that can be used and evaluated for their usefulness in the future.

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506 Lorimer St,
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Anthropometric Manikins for the Design and Evaluation of Soldier Equipment

Executive Summary

Currently soldier systems engineers often use a typical tailor's dummy to design and evaluate torso borne Soldier Combat Ensemble (SCE) items like harnesses and chest rigs. It is not known how the dummy's size and shape was established, but it is likely not based on current Australian Army anthropometric data. Options for sizing design and assessment are based on an analysis of univariate statistics, or more rarely user trials that feature fitmapping to see who fits in what. Univariate statistics are easy to use, but do not represent the complexities of shape or the way in which different anthropometric measures combine. Fitmapping activities are the gold standard of sizing trials, but are extremely labour and resource intensive. Further, few people have the knowledge to conduct these activities.

During 2012 Defence Science and Technology (DST) Group worked with the University of South Australia to deliver the Australian Warfighter Anthropometry Survey (AWAS), the first survey of the Army since the 1970s. This survey contained 85 measures and included full body scans from a Vitus XXL scanner. The results of this survey are used in the design and evaluation of Army soldier equipment and vehicles.

Principal Components Analysis is a common way for reducing a high number of anthropometric variables to a lower number of factors that represent the majority of variance in the dataset. Once the desired accommodation ellipse is drawn around this data, boundary cases can be identified that represent the extremes of the intended user group which are the harder to fit people in terms of shape and size. The theory is that if all boundary manikins can be accommodated by a design then it is likely that those persons within the bounds are also accommodated.

This report contains details of the use of the Principal Components Analysis method to select scans from the Army anthropometric database and then manufacture them into manikins. Some recommendations are made for their use in a design and evaluation context and conclusions and recommendations are made concerning potential ways ahead in the future.

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1. Introduction

1.1 Background

Currently soldier systems engineers often use a typical tailor's dummy to design and evaluate torso borne Soldier Combat Ensemble (SCE) items like harnesses and chest rigs. It is not known how the dummy's size and shape was established, but it is likely not based on current Army anthropometric data (waist circumference is 865 mm, chest circumference is 1005 mm equating to 46th and 49th male percentiles respectively). Options for sizing design and assessment are based on an analysis of univariate statistics or more rarely user trials that feature fitmapping to see who fits in what [1]. Univariate statistics are easy to use, but do not represent the complexities of shape or the way in which different anthropometric measures combine, there is no such thing as the 5th percentile person [2]. Fitmapping activities are the gold standard of sizing trials, but are extremely labour and resource intensive. Further, few people have the knowledge to conduct these activities.

During 2012 Defence Science and Technology (DST) Group worked with the University of South Australia to deliver the Australian Warfighter Anthropometry Survey (AWAS), the first survey of the Army since the 1970s. This survey contained 85 measures and included full 3D body scans from a Vitus XXL[1] scanner. The results of this survey are used in the design and evaluation of Army soldier equipment and vehicles [3].

Principal Components Analysis (PCA) is a common way for reducing a high number of anthropometric variables to a lower number of factors that represent the majority of variance in the dataset. Once the desired accommodation ellipse is drawn around this data, boundary cases can be identified that represent the extremes of the intended user group which are the harder to fit people in terms of shape and size. The theory is that if all boundary manikins can be accommodated by a design then it is likely that those persons within the bounds are also accommodated. This technique has been used by DST to build more representative Digital Human Models for the assessment of military vehicles [3].

1.2 Requirement

Given the lack of representativeness of the tailor's dummy and the availability of the AWAS body scan database, it was requested that some more lifelike manikins be produced that resemble the variation in shape and size across the Army. In meeting this request, the following high level process was adopted:

1. Initial consultation with engineering and designer representatives to confirm intended use and SCE items of interest.
2. Identification of key anthropometric variables that directly relate to sizing for the intended items of interest.

[1] Vitus XXL, Human Solutions GMBH

3. Principal Components Analysis to reduce the number of anthropometric variables to a smaller number of factors that represented the majority of the size variance.
4. Body scans from the AWAS dataset selected based on the boundary cases by the Principal Components Analysis.
5. Manikin production and delivery.
6. Manikin usage capture and development of future options.

This report sets out the detail of this process and then provides conclusions and recommendations for future work, since the overall aim of this work is to evaluate this new method for its utility.

1.3 Digital Methods

Whilst an exhaustive search has not been conducted, it is known that a number of digital methods exist for the design and evaluation of civilian garments that may be employed for torso borne soldier equipment [4]. What they aim to do is generally provide a capability to virtually design and trial clothing against a variety of manikins. The aim is to cut down time to market and prototyping costs.

Whilst the fidelity of these software programs is always improving, there is a paucity of evidence that they provide the levels of information that can be gathered from a traditional fit-map exercise with real people. Further, soldier equipment is frequently designed from a wide range of materials that have differing physical properties such as stiffness and conformability. These aspects are not considered to be well represented within virtual size testing at present. Lastly, the target end user soldier engineers and designers work almost exclusively in a physical medium, designing patterns and cutting materials in a workshop. Providing physical manikins was therefore considered to be the easiest way to integrate the anthropometric data into their current ways of work. Increased provision of simple to use design tools for non-expert users of anthropometric data was identified as one of the key issues in increasing the usage of these data during a recent workshop at the 2015 International Ergonomics Association Triennial Congress [5].

2. Manikin Selection and Production

2.1 Anthropometric Measurement Selection

One of the most important decisions in the preparation of a dataset for a PCA is the selection of measures. The measures should relate to the intended application environment whilst also representing expected combinations. Further it is desirable to remove measures that are heavily correlated with each other, and rely on a representative single measure since highly correlated (and redundant) variables could influence the alignment of the principal component axis system and erroneously define the principal components [6]. Using these principles an initial and then refined list of measures was constructed.

2.1.1 Initial Measures

Initial measurement list was constructed based on commonly used measures for the following items: backpacks, body armour, harnesses, belt rigs and chest rigs. All items relate to torso measurements, therefore these were isolated within the AWAS dataset [3] (Table 1).

2.1.2 Refined Measures

A correlation analysis was run on the measures above and a correlation coefficient of $R \leq 0.85$ was selected as a general threshold for unacceptable correlation between two or more measures. The results of this analysis can be seen in Table 2.

*Table 1.	Table showing initial list of anthropometric measures*

M01 Cervicale Height	Standing surface to Cervicale.
M02 T2 Height	Standing surface to 2nd Thoracic Vertebrae
M03 Acromion Height	Standing surface to Acromion Right
M04 Suprasternale Height	Standing surface to Suprasternale
M05 Substernale Height	Standing surface to Substernale
M06 10th Rib Height	Standing surface to Tenth Rib
M07 Illiocristale Height	Standing surface to Iliocristale
M17 Biacromial Breadth	The horizontal distance between the Acromion (Right) and Acromion (Left)
M18 Bideltoid Breadth	The horizontal distance between the lateral margins of the upper arms on the deltoid muscle
M19 Chest Breadth	The maximum horizontal breadth at the height of Bustpoint, Right (females) or Thelion, Right (males)
M20 Chest Depth	The horizontal distance between the Bustpoint, Right (females) or Thelion, Right (males), and point on the back at the same level.
M21 Bicristale breadth	The distance between the most lateral points on the right and left iliac crests, immediately below the Iliocristale (Right) and Iliocristale (Left) landmarks
M23 Abdominal Extension Depth	The horizontal distance between the Abdominal Point, Anterior, and point on the back at the same level
M24 Hip Breadth Sitting	The maximum breadth of the seated subject at the hip or thigh, whichever is larger.
M33 Chest Circumference	The circumference of the chest at the height of the Bustpoint, Right (females) or Thelion, Right (males).
M34 Chest Circumference (below bust) (female only)	The circumference of the chest at the height of the Inferior Breastpoint (females only).
M35 Waist Circumference (Omphalion)	The horizontal circumference of the torso at the height of the Waist (Omphalion) Anterior.
M38 Stature	The vertical distance between the standing surface and the Top of the Head landmark.
M40 Weight	Mass
M50 Back width	The point-to-point distance between the digitally-extracted Posterior Horizontal Scye, Left and Posterior Horizontal Scye, Right landmarks
M51 Back Length	The contour distance between the digitally-extracted Cervicale and Back Length Marker landmarks.
M85 Front Length	M04 Suprasternale Height minus M07 Iliocristale Height
M59 Hip Circumference	The horizontal circumference of the torso at the height of the digitally-extracted Hip Marker landmark.

Table 2. Table showing initial list of anthropometric measures, the highest correlation with other measures in the list and the decision about whether to retain the measure in the PCA.

Measure	Male Highest Correlations	Female Highest Correlations	Decision
M17 Biacromial Breadth	M18 Bideltoid R=0.71	M18 Bideltoid R=0.53	Retained
M18 Bideltoid Breadth	M33 Chest Circumference R=0.812	M33 Chest Circumference R=0.79	Retained
M19 Chest Breadth	M33 Chest Circumference R=0.727	M33 Chest Circumference R=0.782	Retained
M20 Chest Depth	M33 Chest Circumference R= 0.868	M33 Chest Circumference R=0.912	Removed
M21 Bicristale Breadth	M35 Waist Circumference Omphalion R=0.745	M24 Hip Breadth Sitting R=0.601	Retained
M23 Abdominal Extension Depth	M35 Waist Circumference Omphalion R=0.883	M35 Waist Circumference Omphalion R=0.883	Removed
M24 Hip Breadth Sitting	M59 Hip Circumference R=0.884	M59 Hip Circumference R=0.869	Removed
M33 Chest Circumference	M18 Bideltoid breadth R=0.812	M34 Chest Circumference Below Bust R=0.870	Retained
M34 Chest Circumference (below bust)	N/A	M33 Chest circumference R=0.870	Removed
M35 Waist Circumference (Omphalion)	M23 abdominal extensions depth R=0.879	M33 – Chest Circumference R=0.863	Retained
M38 Stature	Stature is very highly correlated with heights pertaining to body armour placement R>0.9: M01 Cervicale Height, M02 T2 Height, M03 Acromion Height, M04 Suprasternale Height, M05 Substernale Height, M06 10th Rib Height, M07 Illiocristale Height. These measures were removed.		Retained
M40 Weight	Weight was removed from analysis as it is a second order issue. This was preferable to removing the shape variables for which it can be predictor.		Removed
M50 Back width	M18 Bideltoid breadth R =0.712	M18 Bideltoid breadth R =0.703	Retained
M51 Back Length	M38 Stature R=0.586	M38 Stature R=0.549	Retained
M85 Front Length	M51 Back Length R=0.687	M51 Back Length R=0.638	Retained
M59 Hip Circumference	M35 Waist Circumference Omphalion R=0.856	M24 Hip breadth sitting: R=0.869	Male : Removed Female: Retained

2.2 Principal Components Analysis

2.2.1 Software

The software used for the Principal Components Analysis was Multivariate Accommodation Method (MAM) Version 3 written by Gregory Zehner (Wright Patterson Airforce Base).

2.2.2 Male Population data

Of the 1861 available male measurement profiles, 1850 were retained for the analysis due to missing values. Table 3 presents the eigenvalues and the percentage of variance accounted for by each principal component, whilst Table 4 conveys the relative loadings of the individual measures to each component.

Table 3. Table showing Male PCA Principal Components and Eigenvalues

Principal Component	Eigenvalue	%Variance Explained	Cumulative %
1	5.32345	53.23	53.23
2	1.69020	16.9	70.13
3	0.83101	8.31	78.44

Table 4. Factor Loadings for Male PCA

	Factor 1	Factor 2	Factor 3
M17 Biacromial Breadth	0.69874	-0.08912	0.61083
M18 Bideltoid Breadth	0.88713	0.17779	0.18427
M19 Chest Breadth	0.80479	0.28683	-0.04292
M21 Bicristale Breadth	0.79913	0.06878	-0.24576
M33 Chest Circumference	0.87129	0.26276	-0.16453
M35 Waist Circumference	0.80031	0.29008	-0.37888
M38 Stature	0.55842	-0.57648	0.22801
M50 Back Width	0.76204	0.22715	0.19879
M51 Back Length	0.51811	-0.73152	-0.11543
M85 Front Length	0.44866	-0.70101	-0.29369

It can be seen from Tables 3&4 that the first component represents the majority of the variance (53.23%), the factor loadings in Table 3 show that this factor accounts for overall torso size and breadth since loadings are high value for these dimensions. The second principal component accounts for a further 16.9% of the variance and the loadings bias towards measures of torso length.

2.2.3 Female Population Data

Of the 277 female measurement profiles, 239 were retained for the analysis due to missing values. Table 5 presents the eigenvalues and the percentage of variance accounted for by each principal component, whilst Table 6 conveys the relative loadings of the individual measures to each component

Table 5. Table showing female PCA Principal Components and Eigenvalues

Principal Component	Eigenvalue	%Variance Explained	Cumulative %
1	6.16496	51.37	51.37
2	2.18346	18.19	69.56
3	0.89529	7.46	77.02

Table 6. Factor Loadings for female PCA

	Factor 1	Factor 2	Factor 3
M17 Biacromial Breadth	-0.54456	0.38012	-0.65477
M18 Bideltoid Breadth	-0.92085	-0.07789	-0.15018
M19 Chest Breadth mm	-0.84018	-0.16698	0.03461
M21 Bicristale Breadth mm	-0.72289	0.15159	-0.04511
M33 Chest Circumference	-0.87665	-0.27711	0.20629
M34 Chest Circumference Below Bust	-0.88283	-0.17526	0.15684
M35 Waist Circumference	-0.88289	-0.27423	0.1246
M38 Stature	-0.38313	0.72466	-0.23696
M50 Back Width	-0.74314	-0.06999	-0.14434
M51 Back Length	-0.20679	0.82934	0.22612
M59 Hip Circumference	-0.83148	0.00349	0.16936
M85 Front Length	-0.17728	0.76255	0.44866

For females, the first component represents 51.37% of the variance, with the second component accounting for a further 18.19%. The third component adds only 7.46%. As with the male PCA the first component broadly represents overall torso size and breadth whilst the second more heavily loads onto measures of torso length.

2.3 Manikin Selection

The first consideration in the selection of manikins from the PCA analysis was the amount of accommodation desired. Whilst the central 90% has frequently been used in functional performance specifications especially large military platforms that have many constraints on accommodation [7], this was considered to be too low a boundary for soldier equipment which can be more readily and cost effectively altered to enable higher coverage of the population. 90% accommodation translates to 1 in every 10 soldiers not being accommodated by their equipment. Consequently, an accommodation rate of 95% was selected, equivalent to a minimum 19 out of every 20 Army members being accommodated.

The second consideration concerned the number of Principal Components to retain. Retention of the third component necessarily results in a very high number of boundary manikins, as the boundary itself becomes a three dimensional sphere. The third component also accounts for a minority of the overall variance; therefore, considering the developmental nature of this exercise and the need to keep resulting manikins to a minimum then the first two components were retained for the analysis. The resulting plots and boundary cases can be seen in the plots below for the male analysis (Figure 1). Boundary points are selected from the extremes of the PC1 and PC2 axes and the mid points on the ellipse. The ellipse was set with a radius of R=2.45 for the male sample and R=2.44 for females.

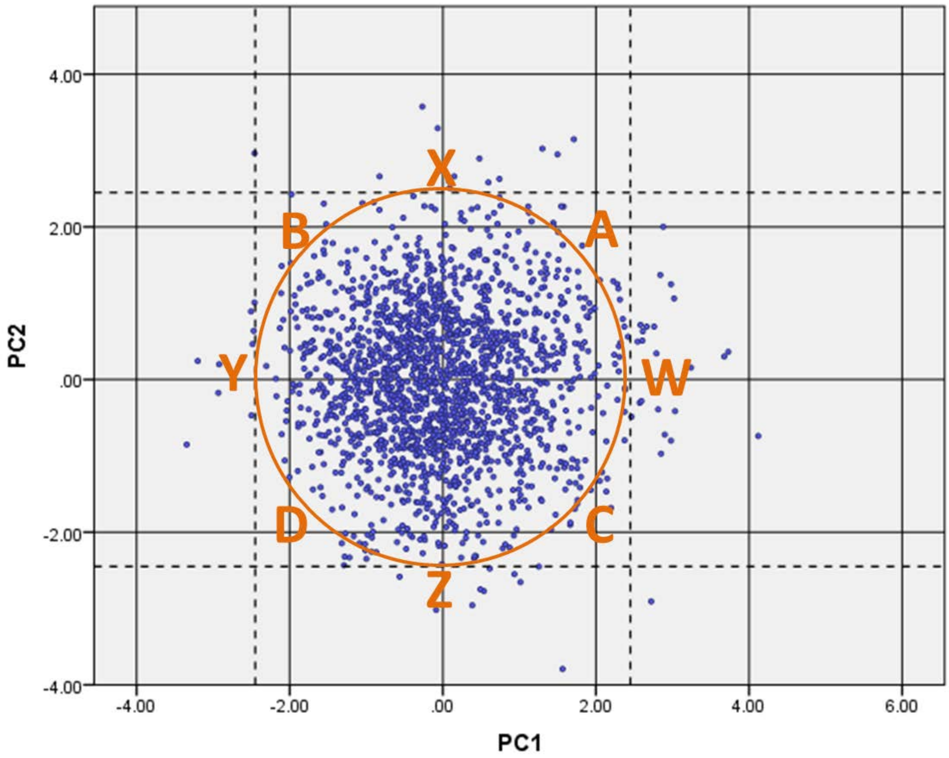

Figure 1. Scatterplot from Male PCA showing boundary ellipse and locations of boundary manikins

Once the points were identified then the nearest neighbours in terms of actual scanned people were selected from the dataset. These were the nearest actual data points to boundary locations in Euclidean distance. Each scan was individually inspected using Cyslice[2].

[2] Cyslice, Headus (Metamorphosis PTY) PO Box 1099, Osborne Park, WA 6916, Australia

After inspection of the scans and data, two male scans were removed as being too similar in shape to the others and therefore adding little to the analysis. Two female scans were retained, being the overall largest and smallest and representing some of the extremes of breast size and hip circumference. These decisions were taken after consultation with the end users of the manikins and with due regard to expected upcoming usage. It is recommended that a full set of female manikins is produced, should this technique have utility, in order to represent the differing female shape more comprehensively. Boundary manikin dimensions are presented in Appendix A.

2.4 Manikin Production

Scans were supplied to Special Patterns PTY[3] for 3D printing. Torsos were machined from high density polystyrene and then coated with a thin polyurethane (PU) spray for durability. Two metal rods were inserted through the base at each leg to increase strength for the potential torso borne loads (Figure 2).

After production, some dimensions were checked for agreement with the dimensions from the real people in the database. In summary, it was found the breadths and lengths were within a few millimetres of their expected values, but that circumferences could be slightly larger. This is probably due to two reasons, the first being the lack of compressibility of the manikins to tape pressure and the second being the additive factor of the PU spray around this particular dimension. The mean difference for male manikin chest circumference was 10.54 mm (SD=25.6 mm), the absolute difference was negligible for smaller manikins and most pronounced on the largest manikins suggesting that the PU coating was likely responsible. The accuracy was judged to be acceptable based on a cost benefit judgement; however future manikins might seek to address this issue through correction factors prior to machining or through different materials and manufacturing methods.

[3] Special Patterns PTY, 19-21 Lakewood Blvd, Braeside VIC 3195

Figure 2. Six Male and two Female torso Manikins with existing tailor's manikin on the left. Top Row left-right Males W, Z D, Y. Bottom Row: Female Y, Male X, Female C, Male A. Note that 4 manikins had heads included, these were requested at a later point but did not form part of this analysis.

3. Manikin Usage

In other applications, such as Digital Human modelling assessment of vehicles [8], boundary manikins are simply run sequentially through a series of common tasks and any issues of fit and reach are identified. Proposed usage in a soldier torso borne equipment scenario is similar in principle and proposed usage cases are provided for both evaluation of existing equipment (Figure 3) and design of new equipment (Figure 4). These flowcharts are meant to function as indicative start points for discussion only and require refinement. In reality the process is much more iterative, but is set out sequentially here for ease of reference.

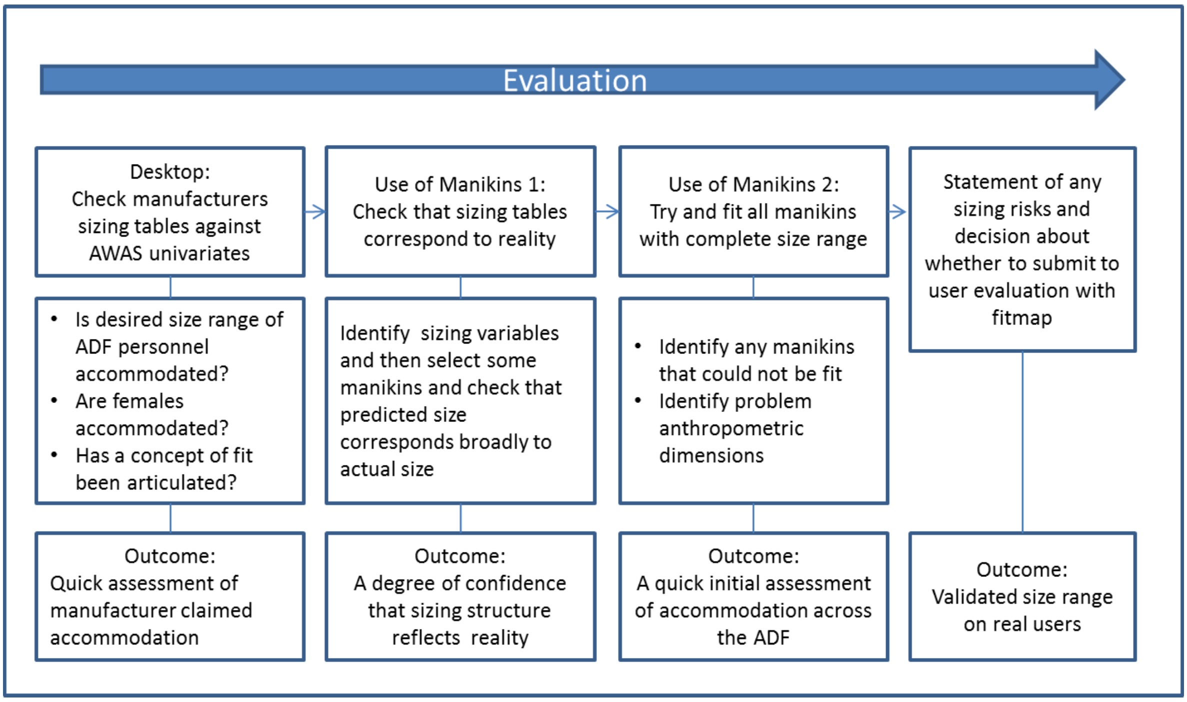

Figure 3. Flow chart for the evaluation of new soldier torso borne equipment using boundary manikins

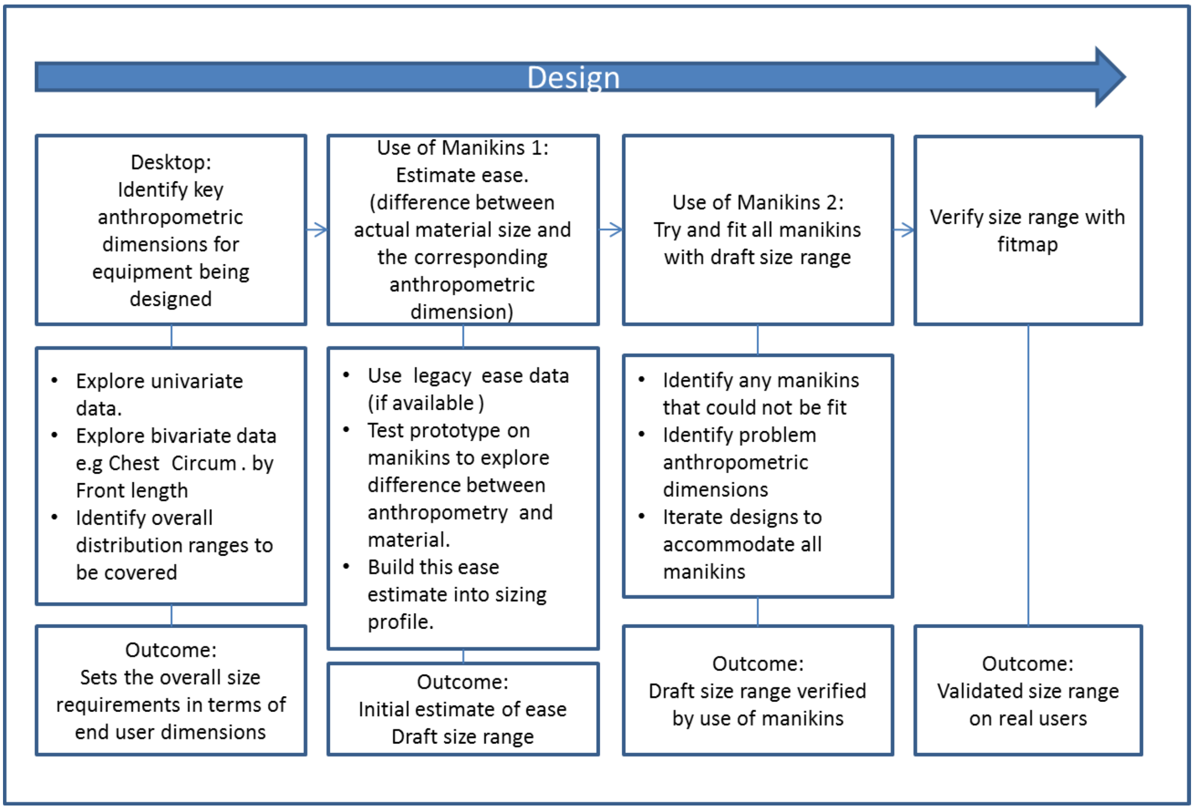

Figure 4. Flow chart for the design of new soldier torso borne equipment using boundary manikins

4. Conclusions and Recommendations

4.1 Conclusions

The manikins have been produced from an established method of statistical reduction, Principal Components Analysis, using body scans from a robust dataset that is representative of the end users of equipment. It is concluded that this is more representative than the tailor's dummy. It is also likely to be more useful than the univariate statistics available because combinations of measures and overall shape are represented.

Principal Components Analysis itself is an exploratory method for data analysis. There are many points where an analyst must make their own judgements about how to progress, examples of these points are:

1. Inclusion criteria for measures in the PCA;
2. Desired accommodation and method for calculation;
3. Number of Principal Components to retain;
4. Body scans to retain.

Some suggestions have been provided for how the manikins may be utilised in the design and evaluation link from data collection to design, this has been based on experience from DST researchers who have conducted similar exercises. However, the link between anthropometric data and end designs is frequently hard to navigate and therefore this should be viewed as a developmental exercise from which pros and cons will need to be established.

The manikins cannot replace a fit-map exercise on real people as they are hard, cannot perform functional movements and are obviously incapable of providing any sort of assessment of subjective levels of comfort and fit.

4.2 Recommendations

It is recommended that this capability be reviewed for utility at a user workshop after there are several examples of its usage. This will allow greater understanding of requirements and iterative improvement based on actual experience of operation.

Subject to the outcomes of the workshop, it is recommended to add a full suite of female manikins as their differing shape from males needs to be more fully represented.

Subject to a cost benefit analysis, it is recommended that future manikins be constructed from materials that more closely resemble the compressibility of human tissue.

It is recommended that a watching brief be maintained on digital programs that may offer a similar capability in the future.

It is a recommended that a higher level of minimum accommodation be established for soldier equipment at 95% accommodation, equating to at least 19 out of 20 soldiers being accommodated by a size range or design.

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Appendix A Manikin Dimensions

	Male A	Male D	Male W	Male X	Male Y	Male Z	Female C	Female Y
M17 Biacromial Breadth (mm)	449	375	434	402	365	419	336	377
Percentile	96	3	82	28	1	59	1	60
M18 Bideltoid Breadth (mm)	595	426	535	517	444	499	395	480
Percentile	99	1	92	79	3	54	2	93
M19 Chest Breadth (mm)	353	264	344	325	274	276	237	319
Percentile	95	4	92	80	10	11	5	96
M21 Bicristale Breadth (mm)	312	286	311	278	255	269	244	294
Percentile	84	44	83	27	4	14	2	77
M33 Chest Circumference (mm)	1169	891	1227	1136	854	960	838	1086
Percentile	98	5	99	95	1	25	18	97
M35 Waist Circ. Omphalion (mm)	1002	758	1173	934	743	809	697	1029
Percentile	88	5	100	72	2	20	5	97
M38 Stature (mm)	1763	1743	1749	1578	1669	1840	1518	1706
Percentile	37	28	31	1	4	80	1	81
M50 Back Width (mm)	400	331	436	400	313	383	294	361
Percentile	87	6	100	88	2	66	12	97
M51 Back Length (mm)	487	485	573	431	437	504	387	467
Percentile	73	71	100	6	10	90	4	90
M85 Front Length (mm)	326	382	379	354	345	429	322	352
Percentile	7	80	76	38	24	100	32	84
M59 Hip Circumference (mm)							872	1183
Percentile							1	90

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19. ABSTRACT

Currently soldier systems engineers often use a typical tailor's dummy to design and evaluate torso borne Soldier Combat Ensemble (SCE) items like harnesses and chest rigs. It is not known how the dummy's size and shape was established, but it is likely not based on current Australian Army anthropometric data. This report contains details of the use of the Principal Components Analysis method to select a representative selection of body scans from the Australian Army Anthropometric survey and manufacture them into physical manikins. The aim is to provide design tools based on real Australian Defence Force member's size and shape that can be used and evaluated for their usefulness in the future.