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Cluster size prediction for military clothing using 3D body scan data

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ABSTRACT

Aim: To determine how anthropometric characteristics cluster in the New Zealand Defence Force, and to describe the characteristics of each cluster. This information can inform the development of new uniform sizing systems for the New Zealand Defence Force.
Methods: Anthropometric data (n = 84 variables) from 1,003 participants (212 females; 791 males) in the New Zealand Defence Force Anthropometry Survey (NZDFAS) were used. The dataset was stratified by gender and variables isolated based on their relevance to shirt and trouser sizing. Principal Component Analysis was used to identify the most important variables for clustering. A combination of two-step and k-means clustering was used to derive cluster characteristics.
Results: The PCA identified optimal clothing (shirt = body height and waist girth; and trouser = inseam length and hip girth for females; inseam length and waist girth for males) variables. Two-step and k-means clustering identified optimal cluster numbers of 6 and 10 for female and male clothing, respectively. The female clothing clusters were more variable (intra-cluster) and further apart (inter-cluster) compared to males.
Conclusions: Anthropometric measurements in combination with clustering techniques show promise for partitioning individuals into distinct groups. The anthropometry dimensions associated with each cluster can be used by the garment industry to develop specific sizing systems for the New Zealand Defence Force population.

1. Introduction

A correctly sized uniform is extremely important for military personnel worldwide. Correct fitting clothing is important for performing various occupational and operational tasks (e.g. pack march, piloting an aircraft), for safety (e.g. body armour protects important organs, chemical suits must fit properly to seal against dangerous liquids or gases) (Keefe et al., 2015) and the ability to provide sufficient mobility and adopting various postures (e.g. using a weapon in prone position). Accurate fitting garments depends on a robust sizing system, the availability of an accurate set of body measurements, and an understanding of anthropometry (Varte et al., 2020; Vuruskan et al., 2011). A clothing sizing system consists of the number of sizes, intervals between sizes, and a size labelling system. It should ensure that the range of sizes fit as much as 95% of the target population (Carr et al., 2012; Keefe et al., 2017a; McCulloch et al., 1998; Zakaria and Ruznan, 2020).

Unfortunately, obtaining the correct fit is challenging due to the vast differences in body types and the variation in body types within a given size interval (Loker et al., 2005). Furthermore, the size intervals may not correspond with real size/shape combinations found in the population. Secular trends show that populations are growing taller (approximately 1 cm each decade) and becoming heavier for the general population (Marfell-Jones and Olds, 2007). These changes in body size and shape also vary by ethnicity, age, and gender (Apeagyei, 2010; Kroemer et al., 1997) and may not necessarily be reflected in current garment sizing systems. Recent increases in the body size of military personnel (e.g. in Australia, Canada and the U.S.) appear to have coincided with changes in body proportions which collectively create additional challenges for maintaining a current and effective uniform sizing scheme (Keefe et al., 2015, 2017b; Knapik et al., 2018; Tomkinson et al., 2009, 2017). In addition to human growth, there has been an increase in the number of females in the military worldwide. Women are increasingly being integrated into military ‘front line’ combat roles in addition to being in long

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standing roles such as air force pilots, search and rescue technicians, and clearance divers. For example, the number of enlisted women in the US military increased by 17% (between 2000 and 2019) to 220,000 (Eagan, 2019). In the New Zealand Defence Force (NZDF), individual service gender targets were set to increase female participation in the Air Force and Navy to 25% and 30%, respectively, by 2025. While the NZ Army is targeting a 25% and 35% increase in females in combat support and combat service support respectively, by 2025 (New Zealand Defence Force, 2019). As a result of the increase in women participation, the female body shape must be considered for clothing and equipment that was originally designed for use by male personnel (Keefe et al., 2017b). The implications of the changes in human growth and demographics in the military will influence clothing design, sizing, and fit.

In military apparel, key measurements or sizing systems are identified from the analysis of anthropometric data of military populations (Carr et al., 2012). The use of 3D body scanners in military surveys have gained in popularity over the last 20 years. Military anthropometry surveys have a long history in the United States, United Kingdom, Australia, and Canada (Kolose et al., 2021) and a growing presence in countries such as Brazil, Indonesia, India, and Iran (Da Silva et al., 2017; Pourtaghi et al., 2014; Purnomo and Kurnia, 2020; Varte et al., 2020). The introduction of 3D body scanners has improved the measurement process immensely. They enable the capture of surface anthropometric data in a time-efficient and non-invasive manner; a larger number of measurements can be taken at once while providing a digital record of the participant (Varte et al., 2020). Numerous studies have investigated the reliability and/or validity of scan-derived measurements compared to more traditional (e.g., ISAK) systems. Body scanners have been shown to measure body volumes, circumferences, and lengths more rapidly and accurately than traditional techniques (Wang et al., 2006). Jaeschke et al. (2015)discovered strong correlations between automatic and traditional measurements for body height; however, the automatic measurements generally ‘overestimated’ most other measurements. Glock et al. (2017) found that body height, waist, upper arm, calf, and hip circumference showed high validity for both traditional and body scanner methods. Choi and Ashdown(2011) found that automatic measurements provided significantly larger values for waist circumference compared to traditional measurements. Alternatively, Wells et al. (2007) found that traditional measurements were more accurate at predicting buttock girth and hip girth.

Clothing measurements extracted from 3D body scans (e.g. sleeve inseam and waist girth) can be used to develop sizing systems. Shape categorisation may use statistical techniques such as principal component analysis (PCA) or cluster analysis (CA) to identify “clusters” of body shapes, develop new size templates, and thus increase the likelihood of a good fit and adequate coverage of the target population (Kaufmann, 1997; Olds and Honey, 2006). Previous research has utilised various types of cluster analysis (e.g. k-means, hierarchical, two-step) to establish sizing charts for the civilian sector such as the New Zealand fire service (Laing et al., 1999) and UK offshore workers (Stewart et al., 2017). These methods have also been used to size uniforms for the Sudanese and Indian militaries (Elfaki and Ali, 2016; Varte et al., 2020), as well as ballistic protection for the Taiwanese and Indonesian militaries (Purnomo and Kurnia, 2020; Wen and Shih, 2020).

Until recently, 3D body scanning technology had never been used to assist garment sizing and selection in the New Zealand Defence Force. In 2019, the New Zealand Army expressed interest in how this technology could optimize their recruit combat uniform sizing process (Kolose et al., 2019). Using the 2016–18 New Zealand Defence Force Anthropometric Survey (NZDFAS) dataset, a previous study was conducted using decision tree models to predict clothing size, using the tailor-assigned clothing size as the gold standard. The study also captured subjective ratings of perceived clothing fit. Findings showed a modest level of size classification accuracy (up to 62%) and a high proportion of perceived poor fitting garments, particularly for females (Kolose et al., 2019). This may suggest inconsistencies between body anthropometry, sex-specific differences in body shape and fit, and the sizing system of the uniform at the time. Now that current 3D anthropometric data (NZDFAS) exists for this population, it may be possible to develop a more adequate sizing system. Therefore, the aims of this study were: (1) to determine how anthropometric characteristics cluster in the NZDFAS data, and (2) describe the characteristics of each cluster. This information may inform the development of a new sizing system for the NZDF.

2. Method

Anthropometric data from the 2016–18 NZDFAS was used in this study (Kolose et al., 2021). The study had ethical approval from the Auckland University of Technology Ethics Committee (AUTEC #14/126 NZDF anthropometry Survey: Variations in kinanthropometry and implications for the New Zealand Defence Force).

2.1. Participants

The NZDFAS dataset was collected between February 2016 and June 2018 and consisted of 1,003 uniformed participants from the Royal New Zealand Navy (n = 131), Royal New Zealand Air Force (n = 289) and the New Zealand Army (n = 583). The participants were recruited from nine NZDF centers across New Zealand using a mixture of stratified (e.g., based on selected demographics such as gender, service, trade, and ethnicity) and purposive (e.g., where a point of contact at each site helped identify participants based on their availability and suitability for the study) sampling.

2.2. Procedures

The data collection consisted of four stages run by a minimum of six staff (receptionist, four trained anthropometrists and a dedicated body scan technician).

(i) Brief, where participants had the study aims explained to them and they completed written informed consent and an electronic demographic questionnaire. This questionnaire captured information such as their service type, years of service, sex, ethnicity, trade, and questions on how they rated the fit of their current uniforms and other military equipment.
(ii) Physical landmarking, where participants had 20 landmarks physically palpated and marked by anthropometrists trained at Levels 1 and 2 by the International Society for the Advancement of Kinanthropometry (ISAK). The landmarks were used to help identify and extract physical and post-processed measurements according to a measurement schedule (Kolose et al., 2021).
(iii) Physical measurements, where participants had 25 measurements (Kolose et al., 2021) taken twice by the anthropometrist using equipment recommended by ISAK (e.g., anthropometer, large sliding calliper, small bone calliper, tape). If the first and second measurements were outside specified limits (i.e., 1% for breadths, length, and girths, 5% for reach measurements) then a third measurement was taken.
(iv) Body scan, where participants were scanned inside the *Vitus Smart XXL®* body scanner (Human Solutions, Kaiserlauten, Germany) wearing tight-fitting underwear (e.g., briefs for males, and sports bra and underwear for females) and a swim cap (to standardise head-related measures such as standing height). Participants were scanned in three different postures (two standing and one sitting posture) whilst wearing stickered landmarks required for post-processed measurements.

The 84 measurements were derived using three measurement methods (automatic, physical, and post-processed) to optimize participant throughput while limiting individual processing times at each data collection activity (Kolose et al., 2021). The measurements were derived

Table 1
NZDFAS measurement methods description.

Method (n)	Description	Hardware	Software	Processing time per individual (min)
Automatic (17)	Measurements are captured using an automatic landmark algorithm. Requires minimum operator effort except for final checking of measurement placement. The software extracts the measurements.	Vitus XXL 3-D body scanner. Human Solutions Ltd.	Anthroscan© software. Human Solutions Ltd.	<1
Physical (25)	Traditional anthropometric measurements conducted by accredited anthropometrists. High operator input (e.g. physical palpation of skin surface) is required. High accuracy dependant on the skill of the anthropometrist.	Traditional anthropometry equipment (callipers, scales, stadiometer).	Excel spreadsheet	30–50
Post-processed (42)	Raw body scans are analysed using a separate software called CySize. The operator extracts the measurements from each body scan using a suite of digital tools (e.g. tapes, rulers). Requires high operator input with specialist skills in 3D anthropometric and digital manipulation.	Vitus XXL 3-D body scanner. Human Solutions Ltd.	CySize™ Headus Ltd	20–30

The number in parentheses in Column 1 refers to the number of measurements in each method. Processing time refers to approximate duration of the activity per participant.

from a combination of various international standards: ISO 7250, ANSUR II, ISAK, NHANES and survey protocols from Australia, UK, Canada and New Zealand (Centres of Disease Control Prevention, 2007; Gordon et al., 2013; International Organization for Standardization, 2008; Keefe et al., 2015; Pringle et al., 2011; Tomkinson et al., 2012). The three methods are summarised in Table 1.

3. Analysis

The analysis was stratified by clothing type (i.e. shirt and trouser) and sex (male and female). Two subsets of data were created by identifying measurements that were related to shirt (i.e. upper body and traditional shirt sizing dimensions) and trouser measurements (i.e. lower body and traditional trouser sizing dimensions). Variables common to both shirt and trouser sizing (i.e. body height and weight) were added to each dataset. Inseam length (calculated as crotch height – 50.8 mm) is regularly used in conjunction with waist girth for sizing military clothing (Brantley, 2020; Dāboliņa et al., 2017; Traumann et al., 2019; Zakaria and Ruznan, 2020) and was thus added to the trouser dataset. See Supplementary file 1 for a summary of all variables (and their respective reference protocols) used in these two datasets and Kolose et al. (2021) for a comprehensive breakdown of each measurement definition and protocol.

These datasets were analysed using principal component analysis and cluster (two-step and k-means) analysis using a similar process to previous work (Bagherzadeh et al., 2010; Tiwari and Anand, 2020). All analyses were performed using IBM SPSS Statistics v24.0.

3.1. PCA

The filtered measurements were analysed using PCA to reduce the dimensionality of the dataset and to determine the variables best suited for the cluster analysis. The Kaiser-Meyer-Olkin measure of sampling adequacy, Bartlett's test of sphericity, and the assessment of the anti-image correlation and communalities matrices were administered to ensure the data were suitable for PCA. The Kaiser-Meyer-Olkin scores were all greater than 0.6, and the Bartlett's test of sphericity were all significant (i.e. female shirt [χ^2 (20672.5) = 2415, p < .01], female

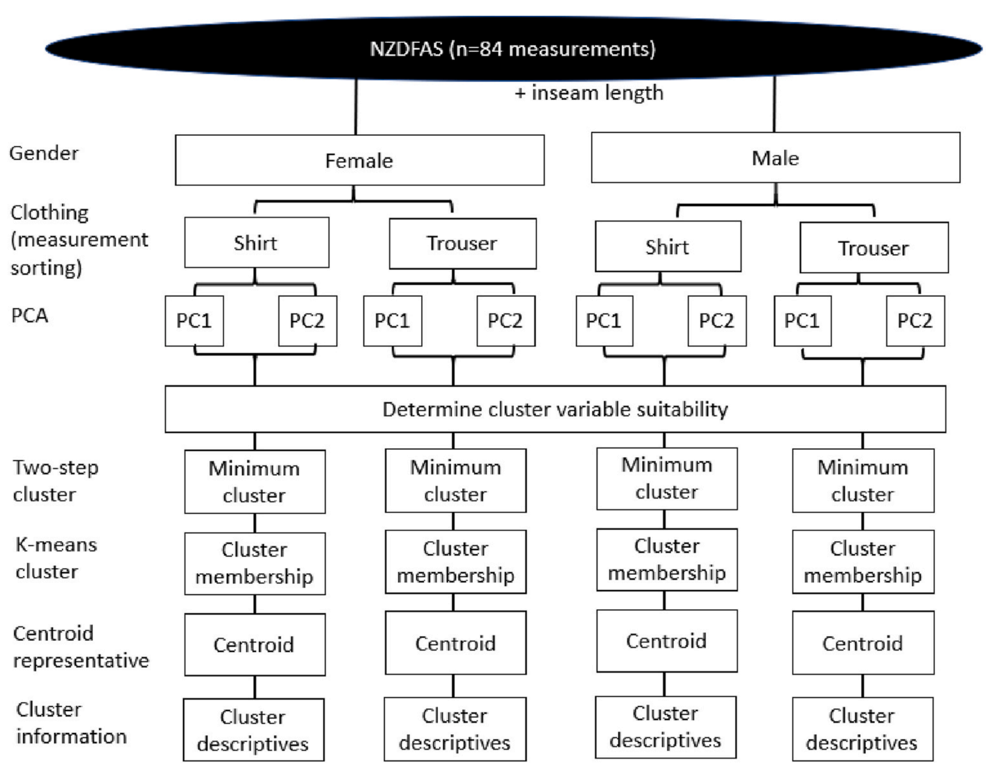

Fig. 1. NZDFAS cluster analysis process for female-shirt, female-trouser, male-shirt and male-trouser datasets.

Table 2
Descriptive characteristics of the NZDFAS sample.

Variable	Level	Male (n = 791)	Female (n = 212)	Total (n = 1003)	P-value[a]
Age		31.6 ± 10.7	30.5 ± 0.4	31.3 ± 10.4	(0.17)
Ethnicity	Asian	22 (2.8)	1 (0.5)	23 (2.3)	(0.14)
	European	327 (41.3)	81 (38.2)	408 (40.7)	
	Maori/Pacific	152 (19.2)	48 (22.6)	200 (19.9)	
	Other	290 (36.7)	82 (38.7)	372 (37.1)	
Service	Army	486 (61.4)	97 (45.8)	583 (58.1)	(<0.001)
	Air Force	217 (27.4)	72 (34.0)	289 (28.8)	
	Navy	88 (11.1)	43 (20.3)	131 (13.1)	
Years of service	<5	331 (46.9)	90 (47.6)	421 (47.0)	(0.67)
	6–10	152 (21.5)	41 (21.7)	193 (21.6)	
	11–15	61 (8.6)	22 (11.6)	83 (9.3)	
	16–20	49 (6.9)	12 (6.3)	61 (6.8)	
	21–25	36 (5.1)	10 (5.3)	46 (5.1)	
	26–30	39 (5.5)	10 (5.3)	49 (5.5)	
	30+	38 (5.4)	4 (2.1)	42 (4.7)	
Trade	Apprenticeship	45 (5.7)	2 (0.9)	47 (4.7)	(<0.001)
	Aviation	32 (4.0)	14 (6.6)	46 (4.6)	
	Combat	170 (21.5)	21 (9.9)	191 (19.0)	
	Engineering/ Technical	225 (28.4)	25 (11.8)	250 (24.9)	
	Hospitality	20 (2.5)	14 (6.6)	34 (3.4)	
	Intelligence IT/ COMS	69 (8.7)	25 (11.8)	94 (9.4)	
	Logistics/ Administration	56 (7.1)	56 (26.4)	112 (11.2)	
	Medical/Health	31 (3.9)	29 (13.7)	60 (6.0)	
	Other	54 (6.8)	19 (9.0)	73 (7.3)	
	Specialist	89 (11.3)	7 (3.3)	96 (9.6)	

Data are presented as mean ± SD or n (%) where appropriate; [a]P-value of difference between males and females (Fisher's exact test or Mann-Whitney *U* test where appropriate).

trouser [χ^2 (9521.4) = 666, $p < .01$], male shirt [χ^2 (82,815) = 2415, $p < .01$], male trouser [χ^2 (41136.4) = 666, $p < .01$]).

3.2. Cluster analyses

3.2.1. Two-step cluster

The variables in the PCA step with the highest loadings that were also deemed practical measurements for clothing sizing were then utilised in the two-step cluster analysis (TSC). Two variables were used for each cluster based on previous cluster studies (Bagherzadeh et al., 2010; Kausher and Srivastava, 2019). TSC was selected because it allows the detection of natural groups within a dataset (in the form of clusters) based on different body types (Majumder and Sharma, 2015), and is frequently used to help simplify high dimensional anthropometric data for the purpose of determining garment size (Bari et al., 2017; Hu et al., 2019; Stewart et al., 2017). The TSC was used to identify the optimal number of clusters for female-shirt, female-trouser, male-shirt and male-trouser datasets by minimising the Akaike Information Criterion (*AIC)* score.

3.2.2. K-means

Next, a k-means analysis was performed using the optimal cluster number and the two main measurement variables used in the TSC. K-means was used to determine cluster membership for each participant in the sample along with the cluster centroids. The body scan image of the individuals with the smallest distance to each cluster centroid were identified as a visual representative of each cluster. Finally, descriptive statistics including the Coefficient of Variation (CV%) percentage (calculated as (stdev/mean)*100) were calculated for the variables used in the analysis, for each cluster. An overview of the analysis process is presented in Fig. 1.

4. Results

4.1. Descriptive statistics

Over half of the participants (58%) were from the Army, and most participants had less than five years of full-time service. European and Other (mainly consisting of those who identify themselves as 'New Zealanders') were the most prominent ethnicities. One quarter of the sample comprised participants from the Engineering and Technical trades. Significant differences between males and females were observed for the proportion of personnel in each of the three services, as well as each trade (Table 2).

4.2. PCA

The first two principal components and their associated factor loadings are presented in Table 3. For female shirt, a height (e.g. eye height, acromiale height, body height) and mixed-dimension component (e.g. waist girth, ab-extension depth sitting, waist breadth), were identified. For female trouser, components related to girth (e.g. buttock girth, waist breadth, waist girth, buttock depth and hip girth) and height (e.g. inseam, knee height, buttock height) were identified. Male shirt consisted of a height (acromiale height, body height, eye height) and a mixed-variable (e.g. waist circumference preferred, waist girth, waist breadth, ab-extension depth sitting) component. For male trousers, a girth (e.g. waist circumference preferred, hip girth maximum) and height (e.g. inseam, knee height and buttock height) component were identified.

Some of the high loading variables identified in the PCA were not suitable to represent their respective component from a logical and practical clothing perspective. For female shirt sizing, eye height and acromial height obtained higher loadings than body height (Table 3). However, both variables would be difficult to measure digitally (acromial height requires physical skin surface palpation, a high degree of skill, and is time consuming) compared to body height (a validated and automatic measurement). We chose waist girth to represent the mixed-variable component for male and female shirt, as it was clearly the highest loading variable except for waist circumference preferred (male). Waist circumference preferred requires user input (e.g. where they would normally wear their belt) and thus deemed too subjective for a reliable clothing measure.

For female trousers, despite obtaining the 5th highest loading within PC1, we chose hip girth to represent the female girth component as it is commonly used in female garment manufacturing and previous cluster sizing research (Hsu and Wang, 2007). Buttock girth and waist breadth were the highest loading variables followed by buttock depth in PC1 (Table 3). However, they are not traditional trouser sizing variables as identified in the literature. Waist girth is the only other alternative that is well documented in the clothing literature (Brantley, 2020; Dāboliņa et al., 2017; Zakaria and Ruznan, 2020). For male trousers, waist girth was chosen to represent the girth component (PC1) based on the shortcomings of other high loading variables such as waist circumference preferred (subjective), waist breadth (non-traditional sizing variable), hip girth maximum (more popular for female as opposed to male trouser sizing), and weight (non-traditional clothing sizing dimension; increases in weight do not necessarily amount to increased size). For both female and male trousers, inseam length (calculated as crotch height − 50.8 mm) was chosen to represent the length or height

Table 3
PCA results by gender and clothing type. An asterisk "*" depicts the greatest loading factor within the associated component. Square boxes depict variables selected for clustering.

	Female				Male			
	Shirt		Trouser		Shirt		Trouser	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Eye height	0.92*							
Acromiale height	0.92				0.93*			
Body height	0.91			0.89	0.93			0.91
Neck height front	0.91				0.92			
T2 height	0.90							
Waist girth		0.94*	0.91			0.93	0.91	
Ab extension depth sitting		0.91				0.91		
Waist breadth		0.91	0.92			0.92	0.93	
Waist depth standing		0.89						
Weight		0.88				0.90	0.92	
Eye height					0.93			
Axilla height					0.92			
Waist circumference preferred						0.94*	0.94*	
Hip girth maximum			0.89				0.93	
Buttock height				0.90				0.93*
Inseam length				0.92*				0.93
Knee height				0.90				0.93
Iliocristale height				0.89				0.91
Buttock girth			0.92*					
Buttock depth			0.91					
Chest girth		0.88				0.88		
Variance explained (%)	38.8	17.9	42.5	21.1	42.5	21.1	45.3	22.7
Total proportion (%)	38.8	56.7	42.5	63.7	41.2	60.0	45.3	68.1

component. It was the highest loading variable for female trouser PC2 and ranked second for male PC2. Buttock height had a higher loading score for male but buttock height is also subjective (derived based on the height of the most posterior protruding point of the buttock). Finally, inseam length is regularly used in conjunction with waist girth for sizing clothing and military garments (Brantley, 2020; Dāboliņa et al., 2017; International Standards Organisation, 1977; Traumann et al., 2019; Zakaria and Ruznan, 2020).

As such, body height and waist girth (automated measures based on International Organization for Standardization (1989) were selected to represent shirt in the cluster analysis for both male and female. For female trouser, hip girth (Tomkinson et al., 2012) and inseam length (Brantley, 2020) were selected for use in the cluster analysis. Waist girth and inseam length were selected to represent male trousers in the cluster analysis.

4.3. Cluster analysis

A TSC analysis was performed using the variables identified from the PCA. Based on the TSC results, the optimal number of clusters for female clothing (shirt and trouser) was 6 (*AIC* scores of 141.2 and 140.1, respectively) and the optimal number of clusters for male clothing (shirt and trouser) was 10 (*AIC* scores of 324.3 and 317.8, respectively). The clusters and representative body shapes (based on cluster centroid) for each sex and clothing type are presented in Figs. 2 and 3. The anthropometric variables from each cluster are summarised in Tables 4 and 5.

4.4. Cluster descriptives

4.4.1. Female clothing

For female shirt, cluster 5 represents small individuals based on medium-short stature (<1652 mm) and low waist girth (<786 mm) (Table 4 and Fig. 2) based on visual fit. Clusters 1 and 6 represent medium-size individuals consisting of medium-tall body height (1587 mm–1730 mm) and waist girth (1002 mm–965 mm). Clusters 3 and 4 represent large individuals based on high waist girth (>984 mm) and tall body height (>1714 mm), respectively. For female trousers, cluster 4 covers the widest inseam length range (15 cm) with a low (<1000 mm) hip girth. Clusters 6 and 1 represent medium-large to large individuals based on their high inseam lengths (>711 mm) and medium hip girth values (>1002 mm). Cluster 5 represents large individuals with medium inseam lengths (676 mm–736 mm) and high hip girth values (>1152 mm) (Table 4 and Fig. 2). For shirt, the average CV% for body height and waist girth were 3.93 and 2.07, respectively. For trouser, the average CV % for hip girth and inseam length was 2.22 and 3.24, respectively.

4.4.2. Male clothing

For male shirt, cluster 7 represents small individuals with low waist girth (<830 mm) and the lowest stature range (1609 mm–1778 mm) (Table 5 and Fig. 3). Cluster 10 represent large individuals based on high waist girth values (>1186 mm) with medium stature (compared to other clusters). Clusters 3 and 9 appear to be at the centre and thus represent medium size individuals with respect to both body height and waist girth. For male trousers, cluster 8 represents small individuals based on a

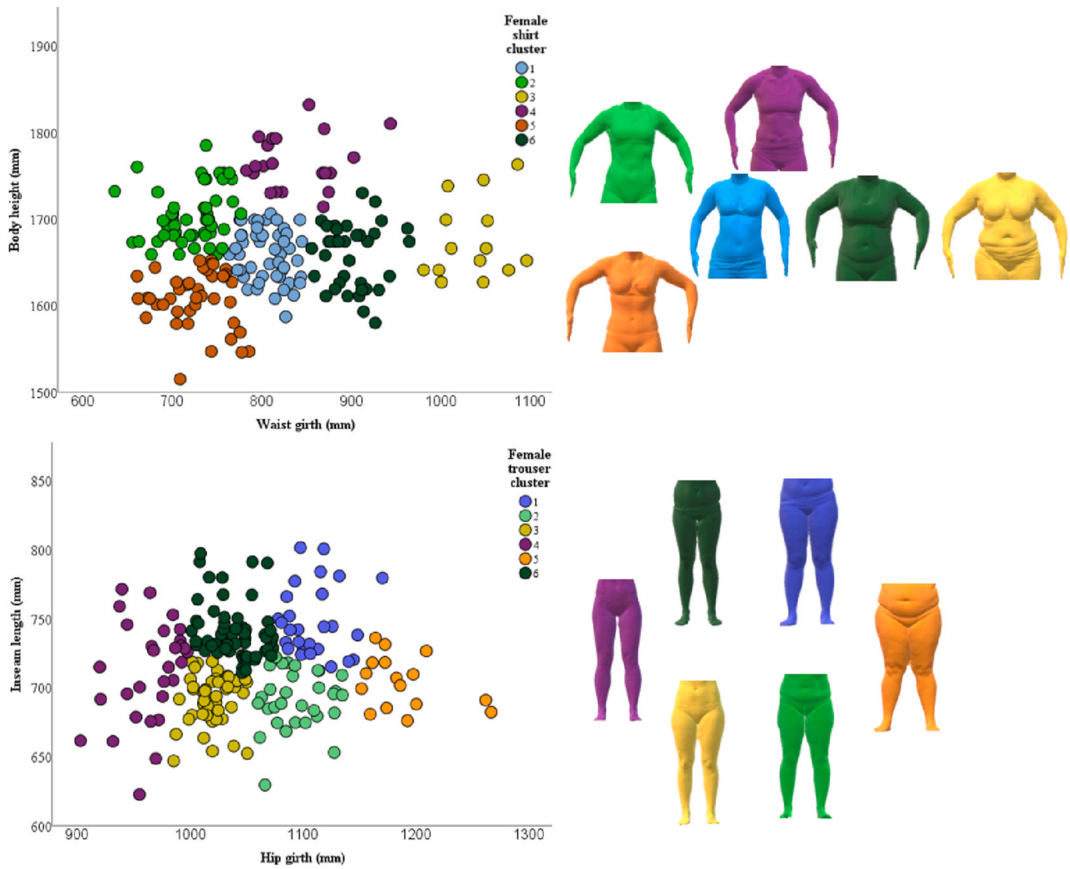

Fig. 2. [Top] Scatter plot showing the different clusters for females shirt (body height vs waist girth) and body shape images representative of each cluster centroid. [Bottom] Scatter plot showing the different clusters for female trousers (Inseam length vs hip girth) and body shape images representative of each cluster centroid.

combination of low inseam length (<758 mm) and waist girth (<808 mm). Cluster 2 represent larger individuals based on high waist girth (>1210 mm) however they have medium to low inseam length (between 710 mm and 795 mm). Clusters 5 and 9 represent medium size individuals based on a combination of both inseam length and waist girth values relative to other clusters (Table 4). For shirt, the average CV% for body height and waist girth were 3.54 and 1.85, respectively. For trouser, the average CV% for waist girth and inseam length was 3.03 and 3.53, respectively.

5. Discussion

The aim of this study was to determine how anthropometric characteristics cluster in the NZDFAS dataset and to describe the characteristics of each cluster. PCA was used to determine key body dimensions for shirt (waist girth and body height) and trouser (waist girth, hip girth and inseam length) clustering. Two-step and k-means cluster analyses were performed on these variables, resulting in 6 and 10 clusters for female and males, respectively.

5.1. PCA findings

In contrast to previous studies (Bagherzadeh et al., 2010; Hsu et al., 2007; Hsu and Wang, 2005) the highest loading variables for the second principal component for shirt (female and male) were not dominated by any one dimension (e.g. it was neither all girth nor all length variables). Hence, PC2 for shirt was named a 'mixed-dimension'. However, the high loading variables for PC2 (waist girth, abdominal extension depth sitting, waist breadth and waist depth) were all related to the lower torso or waist region. This suggests that these variables could be important for garment sizing. The use of waist girth and inseam length for trouser sizing has worked successfully in the past (Elfaki and Ali, 2016; Traumann et al., 2019). We selectively chose alternative measurements for the cluster analyses despite the presence of variables with slightly higher loadings in the PCA. The alternative measurements had minimal impact as loadings for the variables we selected were only marginally lower than the variable with the highest loading (between 0.005 and 0.03 units lower). A surprising finding is that chest girth, a traditional shirt sizing variable, was ranked 6th in the PC2 (female and male) variable loadings. Therefore, waist girth (highest loading variable traditionally used for clothing sizing) was used in the shirt cluster analysis.

5.2. Cluster findings

There were more male shirt and trouser clusters (10) than female (6). When considering gender differences in within-cluster variability for shirt, the male clusters were less variable for waist girth (CV = 3.54 vs. 3.91%) and height (1.85 vs. 2.07%) compared to females. For trousers, males had a higher within-cluster variation for waist girth (3.03% vs. female hip girth of 2.22%) and inseam length (3.53 vs. 3.24%) compared to females. Based on this evidence, a potential female shirt sizing system could have a smaller number of distinct sizes (e.g. four to include S, M, L, XL), while a male shirt and trouser sizing system could have a larger number. However, the higher number of clusters for males compared to females could reflect their respective cohort sizes (791 male verses 212 females). In saying that, we would expect most of these body measurements to be normally distributed in the NZDF population, and there is sufficient evidence that most measurements in the NZDFAS sample are normally distributed for both males and females (see Kolose et al., 2021).

The findings suggest that our cluster data could be used to develop gender-specific sizing systems (as opposed to unisex). The trouser

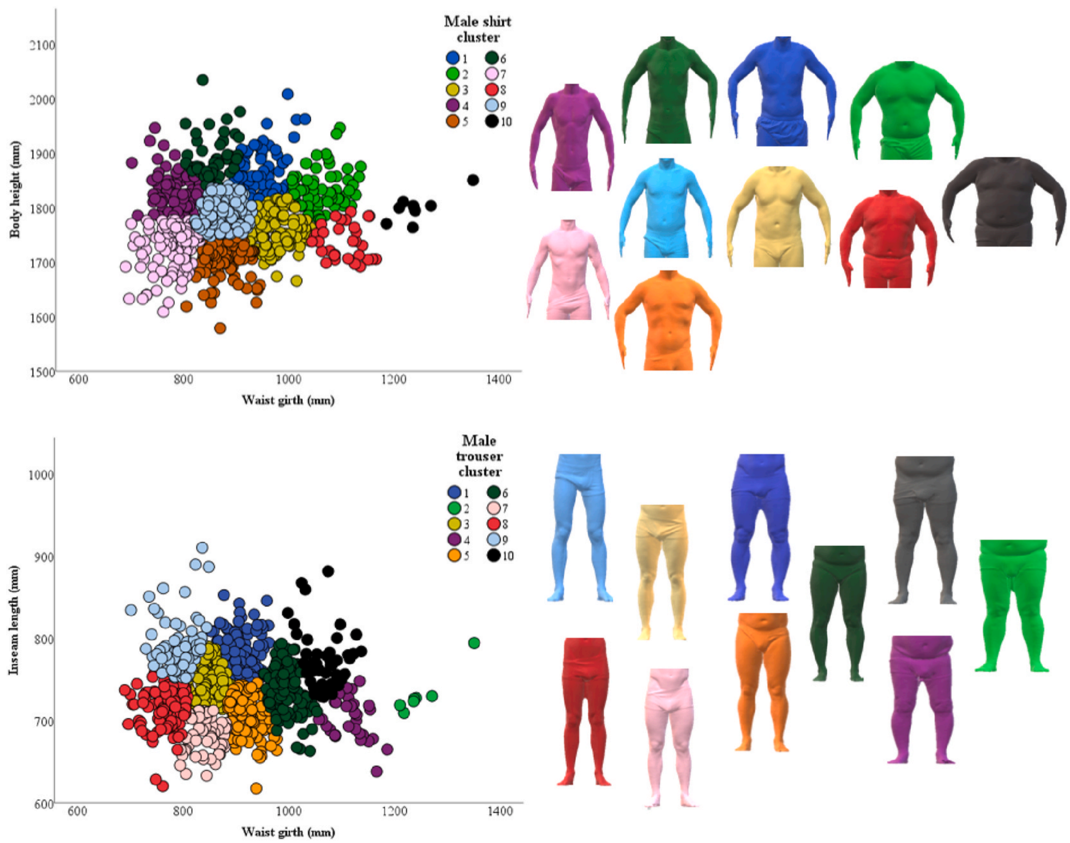

Fig. 3. [Top] Scatter plot showing the different clusters for male shirt (body height vs waist girth) and body shape images representative of each cluster centroid. [Bottom] Scatter plot showing the different clusters for male trousers (Inseam length vs waist girth) and body shape images representative of each cluster centroid.

Table 4
Female shirt cluster number, measurement variable (mm) and descriptives by clothing type.

Clothing/cluster	Variable	N	Mean	S. D	Range	Min	Max	CV%
Shirt Cluster 1	Body height	50	1660	30.1	119	1587	1706	1.81
	Waist girth	50	806	22.8	81	764	845	2.83
Shirt Cluster 2	Body height	49	1704	31.5	126	1659	1785	1.85
	Waist girth	49	722	32.4	141	636	777	4.49
Shirt Cluster 3	Body height	14	1675	45.6	136	1627	1763	2.72
	Waist girth	14	1036	35.6	115	981	1096	3.44
Shirt Cluster 4	Body height	21	1765	30.8	118	1714	1832	1.75
	Waist girth	21	838	43.1	161	783	944	5.14
Shirt Cluster 5	Body height	42	1608	32.8	137	1515	1652	2.04
	Waist girth	42	727	33.9	125	661	786	4.66
Shirt Cluster 6	Body height	36	1658	37.1	150	1580	1730	2.24
	Waist girth	36	901	27.0	109	856	965	3.00
Trouser cluster 1	Hip girth	28	1110	22.9	92	1078	1171	2.06
	Inseam length	28	747	25.1	86	715	801	3.36
Trouser cluster 2	Hip girth	31	1095	23.7	75	1061	1135	2.16
	Inseam length	31	691	20.9	93	630	722	3.02
Trouser cluster 3	Hip girth	48	1020	16.3	65	986	1051	1.60
	Inseam length	48	691	17.7	72	647	719	2.56
Trouser cluster 4	Hip girth	30	965	25.2	95	903	998	2.61
	Inseam length	30	712	36.1	149	623	771	5.07
Trouser cluster 5	Hip girth	16	1188	34.1	115	1152	1267	2.87
	Inseam length	16	704	18.9	60	676	736	2.68
Trouser cluster 6	Hip girth	59	1040	20.8	72	1002	1073	2.00
	Inseam length	59	740	20.3	87	711	797	2.74

Table 5
Male cluster number, measurement variable (mm) and descriptives by clothing type.

Clothing/cluster	Variable	N	Mean	S. D	Range	Min	Max	CV%
Shirt Cluster 1	Body height	66	1870	40.9	193	1816	2009	2.19
	Waist girth	66	947	32.0	135	896	1031	3.38
Shirt Cluster 2	Body height	64	1834	34.4	169	1778	1947	1.88
	Waist girth	64	1063	36.4	131	1006	1137	3.42
Shirt Cluster 3	Body height	107	1761	33.1	152	1666	1818	1.88
	Waist girth	107	979	30.4	116	926	1042	3.11
Shirt Cluster 4	Body height	91	1830	31.5	162	1785	1947	1.72
	Waist girth	91	785	29.8	134	701	835	3.80
Shirt Cluster 5	Body height	94	1704	33.0	167	1579	1746	1.94
	Waist girth	94	879	33.1	140	805	945	3.77
Shirt Cluster 6	Body height	51	1890	39.6	193	1842	2035	2.10
	Waist girth	51	854	28.8	104	803	907	3.37
Shirt Cluster 7	Body height	118	1729	38.2	169	1609	1778	2.21
	Waist girth	118	779	33.1	141	689	830	4.25
Shirt Cluster 8	Body height	31	1738	31.1	101	1692	1793	1.79
	Waist girth	31	1105	36.1	122	1044	1166	3.27
Shirt Cluster 9	Body height	161	1792	24.7	94	1748	1842	1.38
	Waist girth	161	876	26.8	109	821	930	3.06
Shirt Cluster 10	Body height	8	1800	26.5	87	1764	1851	1.47
	Waist girth	8	1244	50.0	165	1186	1351	4.02
Trouser Cluster 1	Waist girth	100	911	24.9	109	853	962	2.73
	Inseam length	100	782	25.8	108	745	853	3.30
Trouser Cluster 2	Waist girth	7	1252	47.8	141	1210	1351	3.82
	Inseam length	7	733	28.1	85	710	795	3.83
Trouser Cluster 3	Waist girth	143	851	20.8	88	806	894	2.44
	Inseam length	143	745	17.5	76	714	790	2.35
Trouser Cluster 4	Waist girth	32	1117	31.0	129	1057	1186	2.78
	Inseam length	32	703	25.1	110	638	748	3.57
Trouser Cluster 5	Waist girth	110	922	24.7	92	885	977	2.68
	Inseam length	110	706	24.3	128	618	746	3.44
Trouser Cluster 6	Waist girth	104	998	24.9	100	953	1053	2.49
	Inseam length	104	737	28.2	131	663	794	3.83
Trouser Cluster 7	Waist girth	60	841	24.7	88	794	882	2.94
	Inseam length	60	684	21.4	79	633	713	3.13
Trouser Cluster 8	Waist girth	101	767	28.7	119	689	808	3.74
	Inseam length	101	714	23.3	138	621	758	3.26
Trouser Cluster 9	Waist girth	84	792	30.2	147	701	848	3.81
	Inseam length	84	790	31.6	159	752	911	4.00
Trouser Cluster 10	Waist girth	50	1067	30.9	139	998	1137	2.90
	Inseam length	50	772	35.1	153	729	882	4.55

variables (e.g. waist girth for male and hip girth for female) also support this separation. However, according to Table 5, some individuals (particularly male) may sit at the border of two or more clusters. For example, a male (1810 mm stature and 980 mm waist girth) may be placed within the common border of three shirt clusters (1, 3 and 9). Varying the cluster input parameters (e.g. using different fixed cluster numbers between 10 and 15) provided no meaningful separation of these clusters. Garment dimensions that are based on the observed clusters could pose problems for these individuals, as they could fall into the upper or lower extremes of a given size category.

Our results are comparable to previous work. Other studies using cluster analysis on anthropometric data for garment sizing have identified a minimum of 3 clusters for female lower body garment sizing (Moon and Nam, 2003) and used chest and waist girth variables to identify 8 clusters for the Sudanese military uniforms (Elnour et al., 2015). In terms of the optimal number of clusters for males, this study had fewer clusters than Purnomo and Kurnia (2020) who identified 19 clusters. These comparisons demonstrate that cluster analysis is a popular method; however, comparisons are difficult to make due to the differences in population-specific anthropometry (e.g. NZ vs Sudanese body size).

5.3. Practical significance

In practical terms, if our six female and 10 male shirt and trouser clusters represented real-world clothing sizes for the NZDF, then it would provide fewer sizes for each sex compared to the NZDF unisex combat uniforms (currently consisting of up to 12 shirt sizes and 12 trouser sizes for Air force, Navy and Army). A reduction in sizes can be beneficial, as more sizes leads to increased costs (e.g. production) and complexity involved in both the manufacturing and the distribution process (Viktor et al., 2006). Clothing manufacturers could design a male and a female variant of the Multi Camouflage Uniform (MCU which is the NZ Army combat uniform that has recently been superseded), with the clothing dimensions for each size based on the cluster descriptives presented here. However, given the creation of separate uniforms for males and females, these decisions are dependent on several external factors, particularly resources (e.g. cost and time of producing new MCU variants).

5.4. Strengths and limitations

Consistent with previous work (Brantley, 2020; Varte et al., 2020), this study examined both upper and lower body measurements separately, with others examining either the whole body (Elfaki and Ali, 2016) or either the upper or lower body (Wen and Shih, 2020). Studying the upper and lower body separately may reduce complexity when interpreting factor loadings during PCA. For example, head circumference may provide a high loading variable for the lower body, despite having no logical relationship with trouser size. The cluster interpretations or labels (e.g. referring to clusters representing small, medium, or large individuals) were subjective. These labels were used in absence of any applied sizing system classification which was beyond the scope of this study.

5.5. Future implications

Future improvements to this study include stratifying the analysis by service (Army, Navy or Air Force), as particular body types may be associated with each service. Given an adequate sample size, the study could focus on specific trades within the defence force (e.g. pilots, navy divers, special forces, or drivers) as these roles may be body-shape specific and require specialised sizing systems. Finally, future work could focus on more specific items of clothing such as body armour. The NZDF and associated industry partners (military garment manufacturers and suppliers) could utilise these results as a foundation for developing a sizing system specific to the New Zealand Defence Force population.

6. Conclusions

Anthropometric measurements in combination with dimensionality reduction and clustering techniques show promise for partitioning individuals into distinct groups; information that is useful for developing sizing systems for military uniform garments. The results suggested that participants could be organised into 6 and 10 clusters for females and males, respectively. The anthropometric dimensions associated with each cluster can be used by the garment industry to develop specific sizing system for the New Zealand Defence Force population.

Authors' contributions

SK was responsible for study design and recruitment, and managed data collection with assistance from AUT and NZDF personnel. SK and PH were responsible for the ethics approval for the NZDF anthropometry survey. Data cleaning and processing were performed by SK and TS. SK performed the analysis with assistance from TS and drafted the manuscript. All authors contributed to the interpretation of results, editing and critical reviewing of the final manuscript, approved the final manuscript as submitted, and agreed to be accountable for all aspects of the work. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.apergo.2021.103487.

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