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# Body Size and ability to pass through a restricted space: Observations from 3D scanning of 210 male UK Offshore Workers.

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## Abstract

Offshore workers are subjected to a unique physical and cultural environment which has the ability to affect their size and shape. Because they are heavier than the UK adult population we hypothesized they would have larger torso dimensions which would adversely affect their ability to pass one another in a restricted space. A sample of 210 male offshore workers was selected across the full weight range, and measured using 3D body scanning for shape. Bideltoid breadth and maximum chest depth were extracted from the scans and compared with reference population data. In addition a size algorithm previously calculated on 44 individuals was applied to adjust for wearing a survival suit and re-breather device. Mean bideltoid breadth and chest depth was 51.4 cm and 27.9 cm in the offshore workers, compared with 49.7 cm and 25.4 cm respectively in the UK population as a whole. Considering the probability of two randomly selected people passing within a restricted space of 100 cm and 80 cm, offshore workers are 28% and 34% less likely to pass face to face and face to side respectively, as compared with UK adults, an effect which is exacerbated when wearing personal protective equipment.

## Keywords

Body size, 3D scanning, bideltoid breadth, chest depth, restricted space

## 1. Introduction

Body size is an important determinant of physical work capability and of space requirements for a range of working environments. Greater space provision may be desirable in order for optimal approaches to physical tasks, and also to provide a sense of ambient space, which may make employees safer and feel more comfortable as they work. A founding design principle of ergonomics is the capacity to accommodate human variability in body size. In order to achieve this aim, the designer will commonly consider the dimensional range in a particular anthropometric measurement (e.g. stature) in the sample in question, and make the design compatible with most individuals. However, if an alternative dimension is selected

(e.g. sitting height), some of those previously accommodated may find themselves disaccommodated depending what the spatial constraints are. This is because different body dimensions are only moderately correlated with one another within a sample, a well recognised academic finding as the lack of 'geometric similarity' for different sized individuals (Nevill et al., 2004). Unsurprisingly, larger individuals in any occupational setting require more space than smaller people in order to move and work, and common practice is to design to the 95<sup>th</sup> centile of male size. However, global variability in size is considerable – with mean height of different adult groups has estimated to be as much as 40 cm (Pheasant, 1986). In addition, individuals from different ethnicities may have different limb proportions as well as absolute size (Holliday & Ruff, 2001), and these factors in addition to the poor correlation between some dimensional measurements can make it difficult to estimate exact size and space requirements. For example shoulder breadth based on the male 95<sup>th</sup> %ile bideltoid breadth, which is frequently used as a design standard for space allocation is reported to vary between 40.0 cm in Sri Lankans and 56.9 cm in Americans (Peebles & Norris, 1998). In addition to nationality, different professions recruit individuals suited to the tasks which favour individuals of different size. While most noticeable amongst elite sports athletes such as basketball players and racing jockeys, increased size, relative to a general population, has been reported in firefighters (Hsaio et al., 2014) and truck drivers (Guan & Hsaio, 2012).

The situation is made more complex when a change in absolute body size is likely within the lifespan of a designed space. This phenomenon is readily apparent when considering historic buildings, ships or furniture, which appear too small when viewed today. In such cases where secular trend in body size, the principle of *design for sustainability* becomes paramount (Nadadur & Parkinson 2013) in order to mitigate the risks of the ill-effects for workers, which need to consider dynamic as well as static spatial needs. Urban planning uses evaluative tools described in Willis et al. (2004) in designed spaces which relate person-flow to a range of factors, including effective corridor width, group size, crowd density etc. They also noted previous work on 'buffer zones' between people and buildings, street furniture and other individuals. In theory, individuals would change their movement behaviour to avoid infringing this zone, preserving a clearance distance which would differ according to the type of object. However the researchers described the difficulty in substantiating and standardising observed variable clearance distances due to differences in experimental design.

In an offshore installation, designs may be more functional than aesthetic. Such environments may have narrow corridors, steep stairwells, exposed walkways and a range of trip and snag hazards more similar to a maritime than an urban environment. The offshore worker necessarily confronts a range of hazards, which are mitigated by strictly enforced procedures – which relate to personal protective equipment, movement around the platform and the response in an emergency. Offshore installations have been in the North Sea since the early 1970s and undergo cycles of inspection and refurbishment, and decisions to provide space beyond the minimum requirements set out by governing legislation need to be balanced against the extra cost incurred. However, to date, consideration of space requirements has not had the benefit of detailed knowledge of shape of actual workers themselves, but rather established databases or design standards which may not represent the workforce accurately.

Offshore workers are subjected to a range of influences which affect their size, with the result that they differ from the host populations from which are recruited. In some circumstances, occupational work itself can provide a training stimulus – especially for the upper body - and differences in physique could be attributed to the training effect of the physical work done. Increasing mechanisation in the latter half of the 20<sup>th</sup> century, has undeniably diminished the 'training influence' of manual work across the population as a whole, however, a range of strenuous roles persist today within the offshore workforce. Strenuous physical work is likely to add muscle, particularly in the upper body and arms, which has the capacity to enlarge the physique considerably. Even amongst workers whose occupational work is not sufficiently strenuous to constitute a significant training stimulus, there may be a culture of strength training in a recreational setting, which may have an equivalent or even greater effect.

In addition to occupational exercise, the global pandemic of obesity has profoundly altered the physiques of working populations. While the secular trend for increasing stature has slowed

since the 1980s to near zero levels, the trend for obesity prevalence and incidence is accelerating rapidly. Defined as an accumulation of excessive body fat, obesity can enlarge all parts of the body, affecting all body dimensions, perhaps with exception of stature itself. Morbid obesity particularly affects the upper body, adding to the volume, breadth and depth of the torso.

In the 1980s, UK offshore workers were observed to be heavier than age-equivalent by between UK reference males by between 1.5 and 4.6% and had higher estimated body fat than an equivalent aged onshore sample (Light and Gibson, 1986). The average UK offshore worker body weight between 1985 and 2009 rose by 19% to 90.9 kg, approximately 9% heavier than the UK male adult average. These findings are consistent with the phenomenon of self-selection of larger individuals, but scrutiny across age groups and years of service would be required to confirm how strong such an effect might be. In addition, there may be a cultural effect whereby food intake and, for some individuals, regular strength training may assume heightened significance. Previous work defined the space footprint via key dimensions (Ledingham & Stewart, 2013), and irrespective of which underlying cause may be more probable, we hypothesised that the UK offshore workforce would have greater bideltoid breadth and chest depth than the UK average, and that for individuals with an enlarged space footprint, egress capability where lateral space is restricted would be correspondingly reduced. As a result, this study aimed to quantify the pertinent anatomical dimensions in offshore workers relative to the general population, and to assess the probability that two randomly-selected individuals are able to pass one another in a restricted space.

## 2. Methods

This study was part of a larger study of the size and shape of UK offshore workers involving 44 university students and staff together with 667 offshore workers. The larger study was in two phases. Phase One involved the university sample and a total of 26 scans for protocol optimisation and scanner calibration, together with the construction of a size-adjustment for moving between the form-fitting and survival suit clothing assemblages. Phase two involved quota sampling across seven weight categories of the male offshore workforce designed to match the weight profile from 2009 data supplied by “Vantage POB” (the personnel and certification tracking system for oil and gas operators). The present study utilises summary data from phase one, and data from 210 offshore workers from phase two, equally representative of all weight categories. Participants were ‘core crew’ whose job entailed 50% or more time being spent offshore, and were recruited via posters and leaflets circulated via Oil & Gas UK and key stakeholders. Measurements were made at various locations likely to ensure a throughput of volunteers, including one offshore installation, heliports, safety training providers, occupational health providers’ and office premises, primarily in Aberdeen, but also in Norfolk which services the Southern North Sea sector. For this each volunteer underwent 3D body scanning using an Artec L scanner (Artec Group, Luxembourg) in a standing position wearing form fitting shorts, and again with a full survival suit and lifejacket over their regular indoor clothing as depicted in figure 1.

Figure 1 near here

Scans were processed using Artec studio 9 software (Artec Group, Luxembourg). This involved global registration, fusion and hole-filling processes, which rendered the scans into 3D objects suitable for measurement extraction. Scans were oriented using a positioning tool which standardised the presentation in 3D xyz space, with the x axis anterior-posterior, y axis lateral and z axis vertical, which enabled co-ordinates to be calculated for all placed landmarks.

Measurements were extracted manually after placing landmarks on the most lateral aspect of convex surface of the deltoid to create a section, and in addition the most anterior point on the thorax when viewed in the sagittal plane. Bideltoid breadth was measured as the maximum point-to-point distance on the section created, and the thorax depth was measured as the horizontal distance in a sagittal plane between the most anterior and most posterior points on

a transverse plane drawn at the maximum anterior extension of the thorax, as depicted in figure 2. These measurement protocols were selected both for their relevance to space requirements, practicality of measurement, and for their compatibility with population data from national surveys.

Figure 2 near here

In order to assess the effect of body size on ability to pass, two theoretical corridor sizes were selected, designed to illustrate the effect of restricted space settings. The probability of the ability to pass without touching was estimated using a simple model from defining a 'space ellipse' projected into a column with vertical sides. Bideloid breadth was used for front-facing, and thorax depth for side-facing strategies. The mean and standard deviation of the variables in question from two individuals selected (assuming a normal distribution) and matching the sum of the measures against the specified corridor width, and mapping the probability of the result against standard normal tables.

The study was approved by Robert Gordon University Research Ethics Subcommittee.

### 3. Results

Participants were aged  $40.5 \pm 10.5$  y, and in indoor clothing (without shoes) weighed  $92.6 \pm 15.9$  kg. Reproducibility of measures was assessed using the technical error of measurement, expressed as a percentage of the measurement value. This was performed independently by two operators on a sample of 21 individuals, and calculated for 'intra-operator' and 'inter-operator' error.

Table 1 near here

Preliminary analyses of 210 individuals were an average of 2.02 kg heavier than the 2009 workforce weight, but the weight distribution of the sample was not significantly different from the 2009 workforce [Sum of  $\chi^2 = 11.1772$ ; Chi-square critical 19.68 (11df); no significant difference between the observed sample and that expected based on the 2009 workforce population distribution].

All participants were measured wearing an appropriately sized survival suit (model 1000, Survitec Group, Aberdeen) and re-breather lifejacket. A size adjustment was previously calculated in a sample of 44 males across a range of body size (Ledingham & Stewart, 2013). This involved extracting measurements from the form-fitting scans for bideltoid breadth, and measuring the equivalent dimensions when they wore the survival suit over regular clothing. This was achieved by orienting the scan in a standard way in xyz space, and creating a transverse section at the deltoid using the same z coordinate for analysis, from which the bideltoid breadth was measured. Wearing the survival suit with regular clothing underneath enlarged the bideltoid breadth by an average of 8.3 cm. The maximum anterior-posterior distance was calculated by the x-coordinate difference between landmarks placed on the most anterior and most posterior aspects of the thorax. Invariably, this landmark fell on the re-breather lifejacket for the anterior mark. Mean increases as a result of wearing the survival suit and re-breather were 18.3 cm. Because the re-breather size and suit thickness are the same across all body sizes, this incremental difference was then applied to the probability calculations for passing ability under different scenarios, as illustrated in table 2.

Table 2 near here

UK offshore workers had bideltoid breadth of  $51.4 \pm 3.5$  cm and compared with  $49.7 \pm 2.9$  cm for UK males reported in Peebles & Norris (1998), a value which exceeds that reported for Americans of  $50.9 \pm 3.6$  cm. Contrast in the chest depth dimensions was greater, with UK offshore workers having  $27.9 \pm 3.2$  cm in the offshore workers, as compared with  $25.4 \pm 2.6$  cm in UK males and  $26.1 \pm 3.3$  cm in US males (Peebles & Norris, 1998).

Based on the UK population, the effect size of the US and UK offshore populations' bidentoid breadths are 0.44 and 0.60 respectively, and for chest depth, are 0.27 and 0.97 respectively. The differences from UK norms of both US males and UK offshore workers are greater at the 95<sup>th</sup> centile than at mean values, and are described in figure 3.

Figure 3 near here

#### 4. Discussion.

Not only does the UK offshore workforce appear to be larger than the UK population, it is also larger than a reference US population which has been commonly considered to represent the largest nation worldwide. The size comparison between offshore workers and UK norms represents a large effect size (Cohen, 1992) at mean values, which appears to be exacerbated at the 95<sup>th</sup> centile. For such employees, wearing a survival suit and re-breather profoundly reduces their capacity to pass one another within a restricted space.

We can be confident in our measurements because the technical error of measurement (TEM) compares favourably with scan-extracted data, and the TEM for both measurements is well below the 1.5% accepted for linear anthropometric measurements adopted for instructor level by the International Society for the Advancement of Kinanthropometry (Marfell-Jones et al., 2013).

Considering the probability of two randomly selected people passing within a restricted space of 100 cm and 80 cm, offshore workers are 28% and 34% less likely to be able to pass face to face and face to side respectively, as compared with UK adults. As a result, estimations of acceptable space based on a generic UK population would grossly underestimate the true space required for an equivalent risk. The effect of wearing personal protective equipment is likely to cause a much greater difference still, for example reducing the probability of two individuals passing by up to 89% in a front-to-side scenario. However, it is appreciated that in a whole range of occupational professions and tasks, the specifics of PPE will vary considerably. In this context, however, the survival suit and its associated lifejacket relates to industry requirements for helicopter travel in the UK continental shelf area. Particularly striking is the effect of the lifejacket on thoracic depth, and the consequent space requirement for mustering, and emergency evacuation.

The ability of two individuals to pass one another was considered by Fruin (1971) who modelled pedestrian space in terms of an ellipse based on shoulder breadth and body depth. His standard was based on the 95<sup>th</sup> percentile male adult worker wearing overalls whose shoulder breadth and chest depth were 55.9 and 33.0 cm respectively. Comparisons are necessarily guarded between the current UK offshore population and Fruin's sample because their precise measurement protocol is not stated, and the magnitude of the size effect of wearing personal protective equipment does depend on its nature and design (Kozey et al., 2009). However, the magnitude of the dimensional difference of the individual equates to an increase of 19% for shoulder breadth and 58% for chest depth, and at face value, the consequent effect on a person's space envelope is considerable. Elsewhere it is stated that the minimum width for moving sideways along a gangway is 33 cm - a value which would equate to the 94<sup>th</sup> percentile unclothed, in our sample of offshore workers. For two individuals to pass (one turning sideways) the minimum width is stated as 76.5 cm at the base and 91.5 cm at the top (Corlett & Clark, 1995). Our data demonstrate that adding the effect of PPE for helicopter travel would render the probability for this passing scenario totally impracticable. Furthermore, because it is well recognised that different occupational groups have characteristically different anthropometric dimensions, the findings of the present study may apply to other professions. Hsiao et al. (2002) identified 'protective service workers' (firefighters, police and guards) as being larger than other occupations. It is also the case, that some of these professions may be the most likely to be associated with working in

restricted space. The ergonomic implications of the convergence of these three factors (enlarged worker size; the wearing of PPE and working in restricted space) cannot be overstated. They have consequences for workplace design and layout, and have an effect of safety dimensions at 'squeeze points' (Corlett & Clark, 1995). This refers to a clearance distance which is not considered a hazard to specific parts of the body provided the distance is not less than a specified value, which for the whole body is stated as 50 cm. In different contexts and under different risk scenarios (such as normal working, v emergency evacuation), this theoretical clearance distance would alter appreciably.

We did not set out to emulate specific building codes in identifying a specific corridor width, nor did we attempt to model the lateral sway of the body which could also be included to inform design guidelines. The US Department of Energy provided guidance for mobile workspace dimensions which include 107 cm as the minimum for two men passing abreast, and 76 cm for two men passing sideways, and a minimum shoulder width of 56 cm in restricted spaces (DOE, 2001). The latter is very close to the 95<sup>th</sup>ile of American males of 56.9 cm from the PeopleSize survey (Peebles & Norris, 1998), and does not allow for lateral sway which Fruin estimated to be "about four inches" (10 cm). Asymmetric load carriage, which may be common amongst manual workers is likely to exacerbate this, and future work in this area may usefully focus on vocationally-specific load carriage, and how compressible clothing layers may be in specific situations.

#### Ergonomic Implications

These findings point to a substantial size difference between UK offshore workers and UK adult norms, with a consequent enlargement of the 'space envelope'. For facilities designed to anticipate a UK normative body size, there is therefore the potential for a considerable mismatch in space provision. The net effect is a reduction in safety distance from infrastructure such as doorways, thresholds and lintels when walking, which will be exacerbated when load carrying. When in a work area, the clearance access from hazard points such as moving machinery, hot surfaces, as well as physical factors such as sharp corners, and other snag hazards is also reduced. Finally, and perhaps most importantly, the performance in emergency situations which demand access and egress to and from restricted spaces, have implications for the wider offshore industry in terms of the speed of egress, and the occupancy of muster stations and lifeboats.

#### 5. Conclusion

Taken together, these findings may have implications for the provision and use of space in offshore installations. This comes at a time when the lifespan of such installations may be extended for the duration of oil recovery in the North Sea. Our data, therefore, directly challenge the principle of design for sustainability, because the clearance space provision will progressively diminish commensurately with the anticipated increase in body size in the future. This has implications for space provision in terms of working space, normal movement within the work environment, mustering space, and the effectiveness of emergency egress.

The lack of recent size information may have created a false sense of security for the UK offshore industry, which requires regulators and operators to consider carefully work patterns both of typically-sized and also larger individuals offshore. While regulatory steps have already been taken to enhance safety both in terms of helicopter seating allocation (in terms of compatibility with windows through which passengers are expected to be able to escape) and lifeboat seating and loading, the same is not true of all aspects of the offshore infrastructure. While our findings remain specific to the male workforce, future size surveys will be necessary to ascertain trends in body size going forward, and these should include female workers whose space needs may differ from those of males.

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## References

- Corlett, E.N & Clark, T.S. (1995). *The ergonomics of workspaces and machines – a design manual*. London: Taylor & Francis.
- Cohen, J. (1992). "A power primer". *Psychological Bulletin* 112, 155–159.
- Department of Energy (2001). Workspace, storage and workshop design. DOE-HDBK pp. 113-117.
- Fruin, J.J. (1971). "Designing for pedestrians a level of service concept" *Highway Research Record* 355, 1-15.
- Guan, J. & Hsaio, H. (2012). U.S. Truck driver anthropometric study and multivariate anthropometric models for cab designs. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 54. 849-871.
- Holliday, T.W. & Ruff, C.B. (2001). Relative variation in human proximal and distal limb segment lengths. *American Journal of Physical Anthropology*. 116, 26-33.
- Hsaio, H., Whitestone, J. Kau, T. Whisler, R., Routley, G. & Wilbur, M. (2014). Sizing firefighters: method and implications. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 56, 873-910. DOI: 10.1177/0018720813516359.
- Hsiao, H., Long, D. & Snyder, K., 2002. Anthropometric differences among occupational groups. *Ergonomics*. 45:2, 136-152.
- Kozey, J. W., Brooks, C. J., Dewey, S. L., Brown, R. C., Howard, K. A., Drover, D., MacKinnon, S., & McCabe, J. (2009). Effects of human anthropometry and personal protective equipment on space requirements. *Occupational Ergonomics* 8, 67–79.
- Ledingham, R. & Stewart, A.D. Volumetric and space requirements of the offshore workforce: The effects of donning a survival suit. *Proceedings of the 4<sup>th</sup> 3D body Scanning Conference, Long Beach California, November 2013*. pp. 317 – 322.  
<https://openair.rgu.ac.uk/handle/10059/1075>
- Light, I.M. & Gibson, M. (1986). Percentage body fat and prevalence of obesity in a UK offshore population. *British Journal of Nutrition* 56, 97-104.
- Marfell-Jones, M., Stewart, A. & de Ridder, H. (2013). *ISAK Accreditation Handbook*. International Society for the Advancement of Kinanthropometry, Upper Hutt, New Zealand.
- Nadadur, G. & Parkinson, M.B. (2013): The role of anthropometry in designing for sustainability, *Ergonomics*, 56, 422-439.
- Nevill, A.M., Stewart, A.D., Olds, T and Holder, R. 2004. Are adult physiques geometrically similar?: the dangers of allometric scaling using body mass power laws. *American Journal of Physical Anthropology*, 124, 177-182.
- Peebles, L. & Norris, B. (1998) *Adultdata: The handbook of adult anthropometric and strength measures*. Department of Trade and Industry, UK.
- Pheasant, S.T. (1986). *Bodyspace: Anthropometry, ergonomics and design*. Taylor & Francis, London.
- Willis, A., Gjersoe, N., Havard, C., Kerridge, J. & Kukla, R. (2004). Human movement behaviour in urban spaces: implications for the design and modelling of effective pedestrian environments. *Environment and Planning B: Planning and Design*, 31, 805-828.

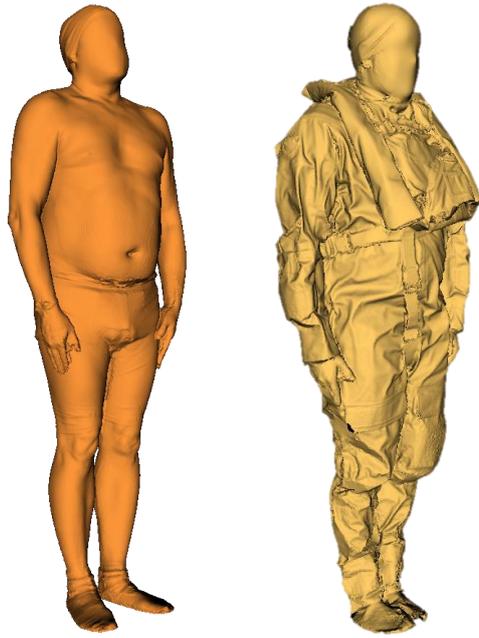


Figure 1. 3D scan position and clothing assemblages

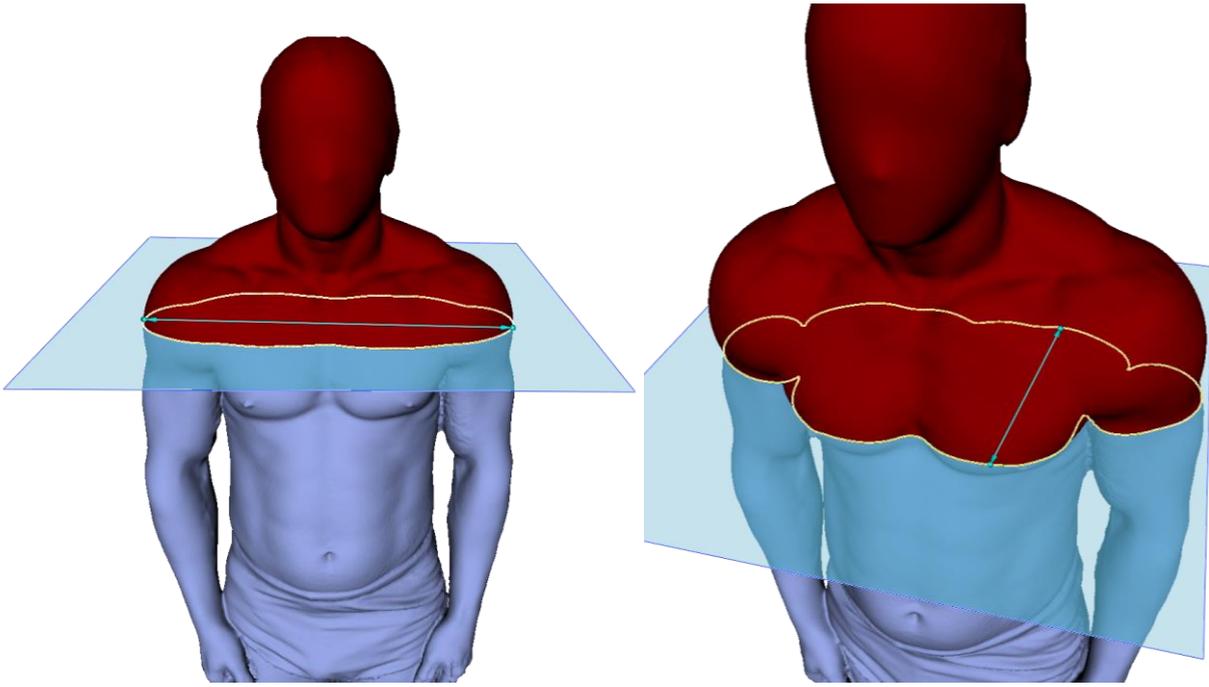


Figure 2. Extracted measurements: L: bideltoid breadth; R: Maximum chest depth

Table 1. Percentage Technical error of measurement

	Bideloid Breadth	Maximum chest depth
Measurer 1	0.47	0.63
percentage intra-operator error		
Measurer 2	0.58	0.60
percentage intra-operator error		
Percentage inter-operator error	0.75	0.82

Table 2. Percentage probability of passing without touching

Form fitting	100 cm corridor	80 cm corridor
F-F	28.5%	0.0002%
F-S	99.9%	55.9%
S-S	100%	100%
Survival suit		
F-F	0.004%	0.0%
F-S	10.5%	0.0%
S-S	95.5%	3.2%

Passing scenarios are F-F: front to front; F-S: front to side; S-S: side to side

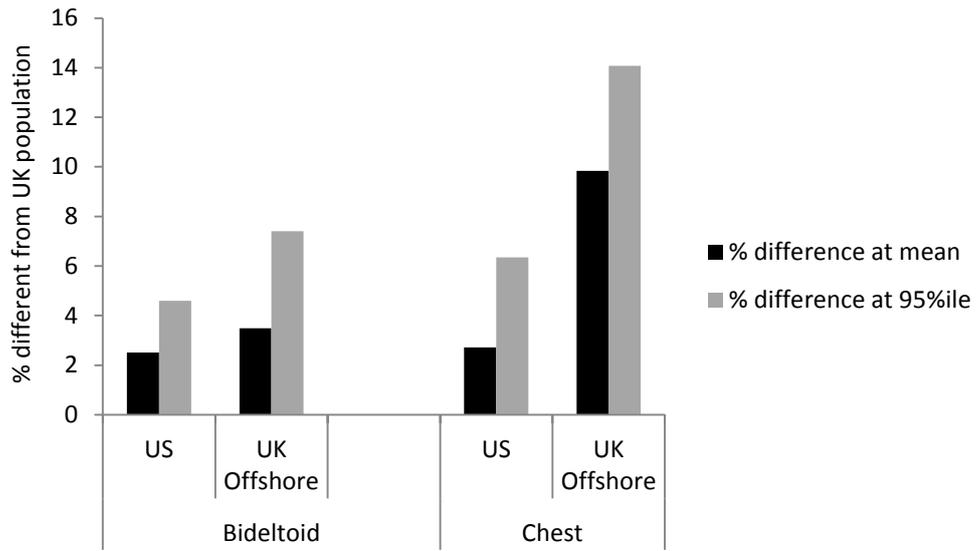


Figure 3. Percentage differences from a typical UK population (PeopleSize)