Minimum aperture transit in healthy adults of different size to predict egress capability

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ABSTRACT

Minimum aperture dimensions have traditionally been considered from an industrial perspective for facilitating safe confined-space working or emergency exit from transportation. However, secular trends for increased typical body size resulting from global obesity mean that clearance space is becoming diminished, and calls into question whether traditional assumptions of space provision are still appropriate. Although this observation has potentially far-reaching consequences for evacuation planning and safe work practices, no current literature describes the minimum frame apertures adults can successfully negotiate. As a result, this study aimed to determine minimum egress apertures in healthy adults of different body size. Forty-eight men and 40 women were recruited from the general public and university manual and academic staff and students. Each underwent anthropometric and 3D scanning assessments from which anatomical dimensions were extracted. A simulated egress task was performed by manipulating an adjustable frame vertically over participants, which was progressively narrowed until individuals failed to pass. Minimum transit aperture was predicted from anatomical variables using backwards elimination regression. This was best predicted from chest depth and bideltoid breadth, plus gender interactions with bicristal (hip) and bideltoid breadths. Passes and fails, discriminated using binary logistic regression, identified mass as the best predictor of success. Minimum egress apertures relate to body size and can be predicted from anatomical variables, however men and women display differences in egress capability which should be further investigated with a contemporary demographic in order to inform future guidelines and legislative change.

KEYWORDS

Body size; anthropometric measurements, aperture transit

Introduction

In certain industries including mining, sewer engineering, shipping and agriculture, legislation exists concerning minimum aperture sizes which aims to ensure sufficient space for the workforce for access and egress. Such guidance seeks to maintain adequate clearance in different body positions (Pheasant, 2003, p47), may target vertically or horizontally-oriented apertures, and may also reflect the depth of the opening to be transited. This varies considerably according to the context, and the regulatory authority. For example 600 x 600 mm is the minimum hatch dimensions for use in agricultural storage (BS 5502-50, 1993). In North America, access hatches must be at least 457 x 610 mm for floors and 407 x 610 mm for vertical walls to provide access to ventilation spaces (International Residential Code R408.4, 2012). The minimum helicopter exit size across the UK fleet servicing the North Sea offshore installations is 432 x 356 mm. (CAA, 2006).

These examples consider adult professionals who will wear specialist personal protective equipment (PPE) as appropriate to the context. By contrast, public settings, catering for all ages of ambulatory people, rarely encompass such restricted space. Public buildings such as museums or libraries are likely to have well designed procedures, which optimise access, circulation and egress, which, more recently have increasingly catered for mobility-impaired individuals. However, exceptions may exist in certain contexts, imposed by unassailable space restrictions and the need to protect public safety. Specifically, certain types of tourist attraction including working or historic mine tours include narrow openings. However, 'prolonged' restricted space is potentially more difficult to negotiate, and prevails in some types of historic building, especially burial chambers. For example, the Maeshowe chambered cairn in Orkney is accessed by a 10 m long tunnel a little over 1 m high. Nearby, the Tomb of the Eagles Mesolithic site (http://www.tomboftheeagles.co.uk/) has a 3 m long tunnel only 75 cm high and 66 cm wide accessed via a trolley-board on which the visitors lie supine. Here, physical restriction may be compounded by psychological insecurity as the entry route is also the exit, which requires that visitors co-operate with one another by returning the board to facilitate access/egress (Stewart & Campbell, 2018). Such locations form a part of an expanding realm of subterranean tourism. They are host to increasing numbers of visitors, which increases the pressure on facilities, and the likelihood of an adverse event involving panic, medical emergency or entrapment. While negotiating these challenging apertures may present little threat to healthy, able-bodied individuals of typical size, it is not safe to assume this is true for all individuals. Critically, it is unknown what clearance space remains when narrow apertures are negotiated by those who are anatomically larger than those of previous generations.

Whether for industrial or public settings, successful aperture negotiation may relate to anatomical constraints of the individual, together with an allowance for movement in relation to the available space. Analysis of clearance space can assess the point at which the ability to pass another person is compromised (Stewart et al., 2015), and, more poignantly, where a single slow moving individual may dictate the speed which everyone behind may progress (Stewart et al., 2017a). Given the importance of providing a safe and enriching experience for visitors, it is perhaps surprising that the tourism market largely self-regulates its attractions. Equally surprising is the paucity of recent literature which can inform the minimum aperture dimensions which individuals of a given size are capable of negotiating. As a result, this study sought to provide baseline data on frame transit in a sample of healthy adults of varying body size.

Participants were recruited from the general public and university manual and academic staff, and students. Forty eight men and 40 women participated, whose physical characteristics are summarised in Table 1. Stature was assessed on a Seca 230 stadiometer, and mass on a Seca 813 digital scale (Seca, Hamburg, Germany). Torso dimensions were acquired using a Campbell 20 large sliding calliper (Rosscraft, Vancouver, Canada) including bideltoid breadth (Stewart & Hume, 2014); chest depth (Stewart & Hume 2015); anterior-posterior abdominal depth and bicristal breadth (Stewart et al., 2011). All measurements were made by a criterion anthropometrist of the International Society for the Advancement of Kinanthropometry. Further dimensional measurements were extracted from 3D body scans (Hamamatsu BLS 9036B scanner (Hamamatsu, Japan), and Artec L (Artec Group, Luxembourg) processed by proprietary software (Body Line Manager 1.3 or ArtecStudio 9, respectively). Wearing form-fitting lycra clothing, participants stood erect with elbows against the side of the torso, with hands against the lateral thighs in a mid-prone position (thumbs forward), with the scan acquired at the end-tidal position. The inferior margin of each deltoid muscle was located to identify bideltoid breadth as the Euclidian distance between the two, and chest measurements were identified as: A) the largest horizontal distance in the sagittal plane across the thorax) and B) the perpendicular planar distance between the most anterior and posterior points on the thorax. Duplicate scans acquired in 20 individuals quantified inter-tester error, with extracted measurements made independently by two members of the research team.

The window transit assembly comprised a rigid wooden frame and two perpendicular and adjustable sliding metal braces as shown in Figure 1. Apertures were systematically varied by altering bolt fixings with colour-coded pre-set spacing, and initial entry aperture was selected based on the participant's bideltoid breadth. In practice, individuals reached through with one arm leading, and the researcher passed the window frame over the participant, who manoeuvred through the appropriate quadrant. Following the successful completion of a trial, the space was reduced by alternately reducing the height or width of the aperture by 2.5cm. If the frame became lodged against the participant, the test was terminated and the frame unbolted. Egress capability was recorded as the smallest diagonal dimension of the frame successfully transited.

Backwards elimination regression analysis was undertaken on log-transformed dimensional variables of shoulders, torso and hips using SPSS v 21 (Chicago, USA), to predict the minimum window frame diagonal from anatomical variables. Binary logistic regression was used to explore which key physical characteristics could predict the odds of failing to pass through apertures at the median minimum size successfully transited. All participants provided informed consent, and the study was approved by the School Research Review Board of the host university.

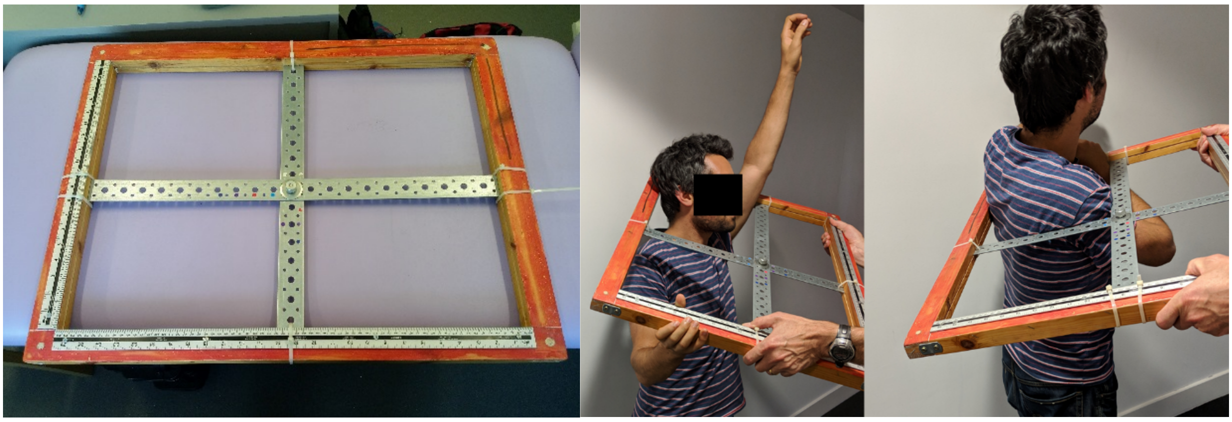

Figure 1. Adjustable window egress frame, which participants pass over their heads, leading with one arm, passing down the torso and legs, and stepping through to score a successful transit.

Results

Participants' physical characteristics are summarised in Table 1.

Table 1. Participants' physical characteristics

	Male (n=48)	Female (n=40)	Total (n=88)	range (n=88)
Age (y)	27.8 ± 10.2	32.0 ± 10.2Ɨ	29.7 ± 10.4	18 - 57
Stature (cm)	177.1 ± 7.0	165.8 ± 6.0**	172.0 ± 8.6	154.5 – 193.5
Mass (kg)	82.6 ± 16.8	66.7 ± 10.3**	75.3 ± 16.3	53.2 – 129.9
BMI ($kg.m^{-2}$)	26.2 ± 4.5	24.2 ± 3.7*	25.3 ± 4.3	18.4 – 41.1

Ɨ NS; Different from males *P<0.05; ** P<0.001

The reproducibility error of measurements quantified by percentage technical error of measurement across the different dimensions was 0.91%, 0.83%, 1.0% and 1.1% for manual anthropometric inter-tester, scan intra-tester, same scan inter-tester, and duplicate scan inter-tester error, respectively, conforming to internationally-recognised standards for experienced measurers.

Backwards elimination regression of all anthropometric variables (manual and 3D) including mass, bideltoid breadth, chest depth, abdominal depth and bicristal (hip) breadth produced the following prediction for frame transit:

$$\text{Ln minimum frame transit (cm)} = 0.168\ \text{LnM} + 0.502\ \text{LnBDs} + 0.118\ \text{LnCDp} + 0.403\ \text{FemalelnBCB} - 0.348\ \text{FemaleLnBDs} + 0.767\quad (R^2 = 0.88;\ SEE=0.028;\ P<0.0001)$$

where M= mass (kg); BDs = bideltoid breadth from scan (cm); CDp = chest depth physique from scan (cm); BCB = bicristal breadth (cm);

Predictability of frame transit, based on the minimum diagonal of the size successfully egressed is depicted in Figure 2. The difference between frame diagonal successfully egressed and bideltoid breadth reduced with age (P<0.001) but showed no effect with BMI or total mass.

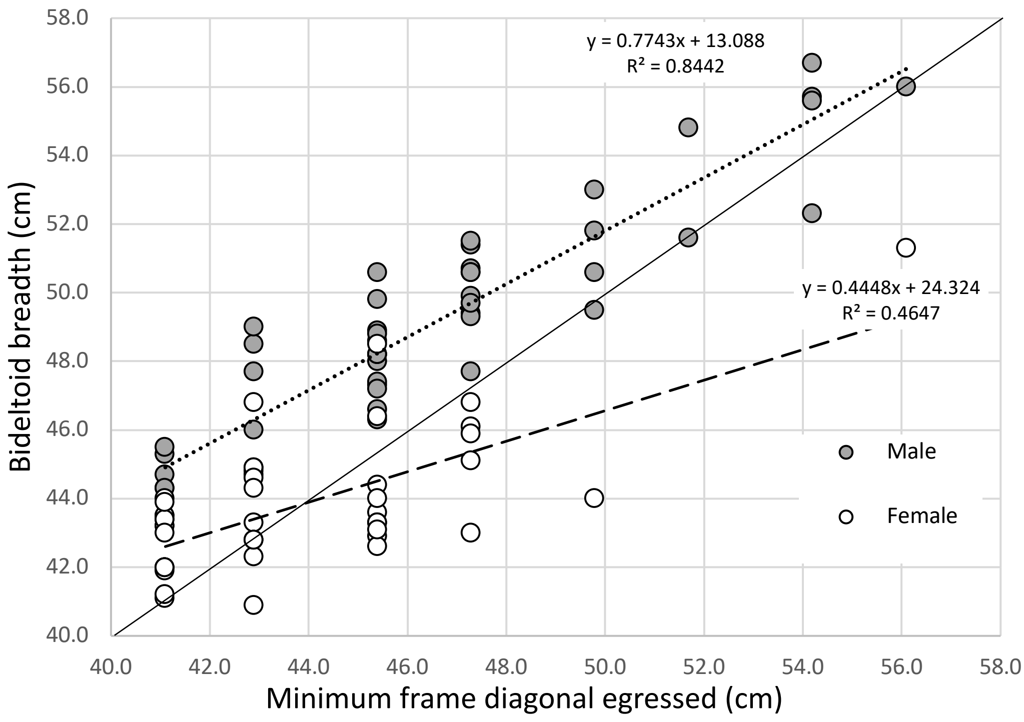

Figure 2. Frame egress capability plotted against bideltoid breadth, showing male and female regressions (solid line represents line of identity)

The difference between the smallest window diagonal successfully egressed and bideltoid breath was typically 2.7 cm greater for men than women (95%CI 1.84 – 3.55 cm; P<0.0001).

Frame transit was investigated relative to a median diagonal value of 43 cm. At this size of frame, 13 men and 23 women passed, while 35 men and 17 women failed. The resulting data from the logistic regression is summarised in Table 2.

Table 2. The key physical characteristics associated with failing to egress through the 43 cm frame

	B	Sig.	Odds Ratio (OR), exp(B)	95% C.I. for the OR	
				Lower	Upper
Mass	.282	.000	1.325	1.177	1.492
Constant	-19.374	.000	.000		
χ^2 test for model coefficients	65.7 (1df)	<0.001			

Lastly, passes and fails for the median successful transit values were compared for a range of dimensions. Standardised effect sizes were calculated and depicted in Figure 3, in a hierarchy of parameters from minimally to maximally different between the groups.

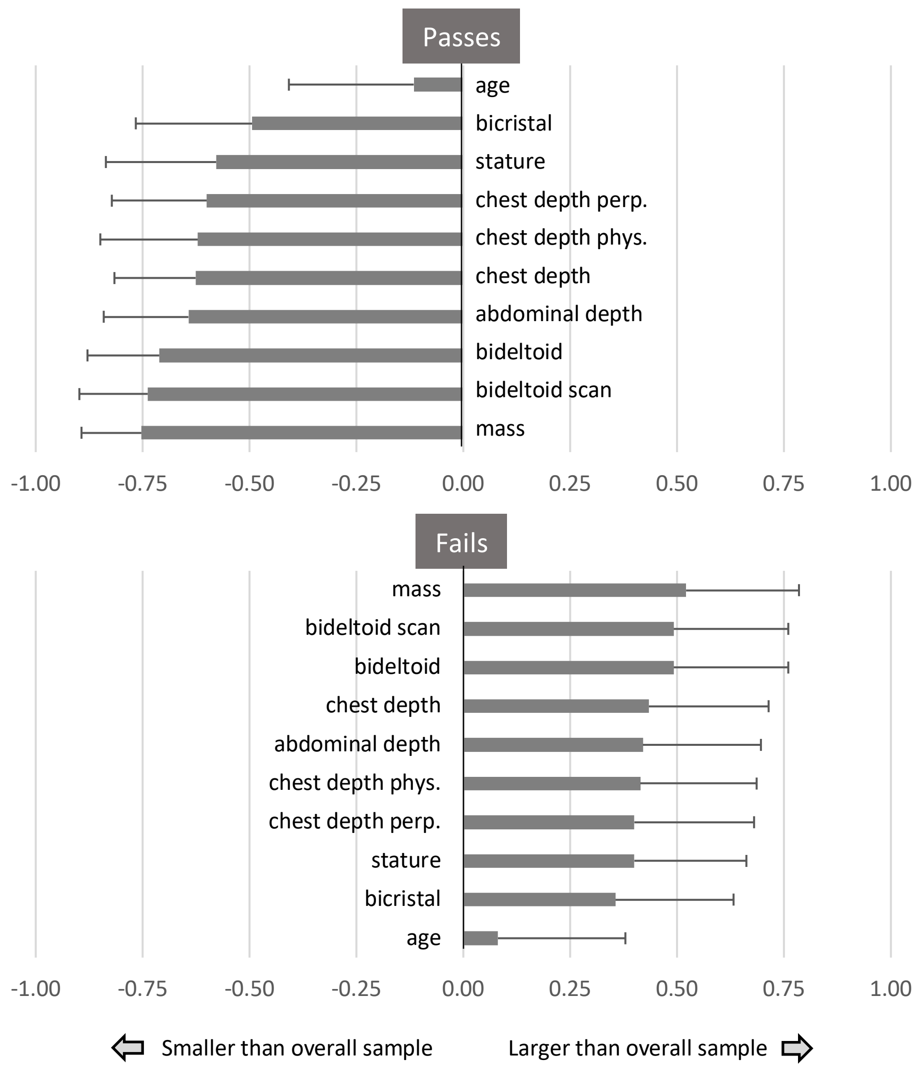

Figure 3. Standardised effect size of passes (n=36) and fails (n=52) of a frame diagonal of 43 cm. Error bars show 95%CI. Variables with a greater horizontal distance between passes and fails indicate their greater capacity to discriminate between them in a predictive test.

Discussion

The main findings of the study demonstrate that frame transit capability can be predicted from body dimensions. Unsurprisingly, successful transit is size-dependent, and using mean anthropometric values from our sample, males successfully egressed a diagonal of 46.7 cm and females, 44.1 cm. However, a subtle gender difference emerges whereby for a given shoulder breadth, males have greater egress capacity than females. Although women are typically smaller than men, it is therefore not always safe to assume their egress capability is equivalent to that of smaller men. As a result of their different morphology, each gender requires special consideration (as identified by the gender interaction). The gender interaction terms selected in the optimised model were the bideltoid and bicristal breadths, suggesting that the morphology of the shoulders and hips were both pertinent in male-female differences in egress capability. For individuals of similar shoulder dimensions, men are capable of egressing through a smaller window aperture than women, as depicted in Figure 2. At face value this might appear counter-intuitive if shoulder-breadth is considered to be derived from skeletal size and overlying soft tissue, if men are expected to have greater muscle and less fat than women at the bideltoid location. Assuming that fat is more compressible than muscle (Toomey et al., 2012) the observed findings cannot be explained by differences in tissue compressibility. There are a number of alternative explanations, which include flexibility, or specific shape attributes which could affect frame transit differently between men and women.

Flexibility. The bideltoid-to-stature ratio was 0.28 for men and 0.26 for women ($P<0.001$), and this suggests that for a given shoulder breadth, stature will be less in men. It is also possible that the men were more flexible than the women in the sample, as has been reported in over 3000 adults across different age categories using multiple tests (Battié et al., 1987). Their study demonstrated that while men tended to have flexibility which exceeded that of women, the results were test-specific and age specific, with the flexibility loss with age greater for men than women. In the current study, greater flexibility in men may partly explain their superior egress capability, but may not be the only factor.

Body morphology and shape. It was apparent that a sizeable minority of women egressing the window succeeded at the shoulders, but ultimately failed at the hips, where the frame became lodged. This occurred in roughly a quarter of cases. A regression of bicristal breadth, the skeletal hip diameter measured when compressing overlying tissue, proved little better than bideltoid breadth. It is possible that a combination of the skeletal hip diameter, plus overlying soft tissue depth may explain these findings. Uncompressed hip diameter (measured against the resting skin surface) may have been a useful parameter to acquire, but this would have necessitated a further body scan, as it is influenced by foot position, as the standard scanner position normally requires a splayed foot position for stability, while the anthropometric position for hip dimensions is normally with feet together (Stewart et al., 2011). In a wider context, the ability to achieve the optimal orientation to facilitate transit may be compromised in late-stage pregnancy (Franchak & Adolph, 2014), and similarly in obese individuals whose abdominal depth approaches or exceeds hip breadth and as a consequence, torso rotation relative to the aperture offers no advantage.

The practical implications for this research. This study contributes baseline data to align with sizing standards for design and an ‘optimised scenario’ for egress modelling. It provides hitherto unavailable information regarding anatomical constraint, which, in respect to fixed-sized apertures together with trends for increased body size, flags an important area of concern for future research.

However, it is important to recognise two fundamental aspects which would preclude these data from being directly transferable to a design standard.

Firstly, the sample comprised apparently healthy, non-pregnant ambulatory adults across a range of body size. As a result, the very elderly and those with clinical conditions for whom participation may have posed additional risk were excluded from participation by the University ethics review board. Therefore, a ‘real life’ scenario which might include such individuals could not be replicated in this experimental approach. Although the study did include a large range of body size from underweight to obese, it stopped short of ‘super-obese’ individuals whose body mass index exceeds 50 $kg.m^{-2}$. It is the ‘super-obese’ who are most likely to be affected by restricted space for transit, and in the USA there is evidence their prevalence has increased tenfold over a 24-year period during which the prevalence of obesity itself (BMI $\geq$ 30 kg. m^{-2}) only tripled (Strum & Hattori, 2013). The implications are that extremely large individuals are likely to become much less rare as a function of this trend in a population of working age, and more common as a direct result of increasing visitor footfall in public spaces. Narrow openings may require negotiation in key industries which have regulations which seek to ensure a margin of safety. The evidence base for this may be specific to occupational groups and PPE, revealing that different professions demonstrate size differences (Hsaio et al., 2002) or they exceed secular trends for increased body size (Stewart et al., 2017b).

Secondly, the frame transit approach, used in aviation research for making recommendations for exit size (Allan & Ward, 1986; Stewart et al., 2016), may not be directly applicable for ‘prolonged’ narrow spaces such as a ventilation duct. This is because the relative body position egressing a frame can be optimised geometrically via a translation combined with rotations in the sagittal and coronal planes. In reality, the longer the transit depth (the thickness of a wall, or length of a duct or tunnel), the more challenging this becomes, because the extent of rotation is constrained by the inner surface. Further, compared to the vertical transit undertaken in the present study, it is more challenging to egress horizontally, with crawling or contrived locomotion, where weight-bearing necessarily uses body structures other than the feet. In terms of an evacuation scenario, individuals may be unable to reach a window they are capable of fitting through, so inevitably the transfer of these findings to specific building configurations is limited.

While previous ergonomic studies have examined clearance space, they may have lacked a robust methodology, and have participant samples which could no longer be considered contemporary. As a result, design standards in use today which make allowances for PPE and a margin of safety may lack validity if they do not consider a minimum egress derived experimentally from a contemporary sample. The present study has shown for the first time that it is unsafe to consider females as equivalent to males as they negotiate narrow apertures. As global obesity increasingly affects both professional groups and the wider public, knowledge of egress capabilities and clearance space required will become increasingly important to ensure safety within public and industrial restricted spaces.

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