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YEAR: 2017

Publisher citation: STEWART, A., LEDINGHAM, R., FURNACE, G., WILLIAMS, H. and COLESHAW, S. 2017. Survival suit volume reduction associated with immersion: implications for buoyancy estimation in offshore workers of different size. Ergonomics [online], 60(6), pages 844-850. Available from: http://dx.doi.org/10.1080/00140139.2016.1188219

OpenAIR citation: STEWART, A., LEDINGHAM, R., FURNACE, G., WILLIAMS, H. and COLESHAW, S. 2017. Survival suit volume reduction associated with immersion: implications for buoyancy estimation in offshore workers of different size. Ergonomics, 60(6), pages 844-850. Held on OpenAIR [online]. Available from: https://openair.rgu.ac.uk

Survival suit volume reduction associated with immersion: implications for buoyancy estimation in offshore workers of different size

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Abstract

Rationale. It is currently unknown how body size affects buoyancy in submerged helicopter escape. **Method.** Eight healthy males aged 39.6±12.6 y (mean±SD) with BMI 22.0-40.0 $kg.m^{-2}$ wearing a standard survival ('dry') suit undertook a normal venting manoeuvre and underwent 3D scanning to assess body volume (wearing the suit) before and after immersion in a swimming pool. **Results.** Immersion-induced volume loss averaged 14.4±5.4 l, decreased with increasing dry density ($mass.volume^{-1}$), and theoretical buoyant force in 588 UK offshore workers was found to be 264±46 and 232±60 N using linear and power functions respectively. Both approaches revealed heavier workers to have greater buoyant force. **Discussion**. While a larger sample may yield a more accurate buoyancy prediction, this study shows heavier workers are likely to have greater buoyancy. Without free-swimming capability to overcome such buoyancy, some individuals may possibly exceed the safe limit to enable escape from a submerged helicopter.

Keywords: survival suit; body volume; estimated buoyancy; offshore workers; 3D body scanning

Practitioner Summary

Air expulsion reduced total body volume of survival-suited volunteers following immersion by an amount inversely proportional to body size. When applied to 588 offshore workers, the predicted air loss suggested buoyant force to be greatest in the heaviest individuals, which may impede their ability to exit a submerged helicopter.

Introduction

The UK continental shelf is host to a large offshore oil and gas workforce which travels to the installations throughout the sector by helicopter. This necessitates wearing a survival suit and lifejacket / breathing system which is designed to maintain the wearer's deep body temperature in the unlikely event of a ditching in the cold waters of the North Sea. Suits worn by helicopter passengers and crew must comply with a series of requirements which relate to materials, fastenings, seals, thermal protection and buoyancy from the European Aviation Safety Agency. For example ETSO 2C 503, (2006) relates to the performance of immersion suits in combination with lifejackets. This includes factors such as being able to undertake jump tests, turning tests, life raft boarding and underwater escape through a restricted opening. Although the maximum permitted buoyancy attributable to trapped air inside suits is 150 N (tested in accordance with ISO 15027-3:2002), the ease with which a person can move below the water surface is governed by the total buoyancy of the person, which, in addition to inherent buoyancy of all garments, is influenced by body composition together with the residual air in the lungs and GI tract (McArdle, Katch & Katch, 2001, p 772).

When rotorcraft ditch into water, unless the sea state is fairly calm, their high centre of gravity means that they tend to invert and consequently sink (Brooks, 1989). Under such circumstances, flight crew and passengers, when released from their seatbelts, require to overcome buoyant forces in order to make an escape through an exit below the water surface; a task which is particularly challenging due to poor visibility, disorientation, and extreme anxiety induced by the accident (Brooks 1988). Air which remains trapped inside the survival suit adds to the buoyancy, and the greater the buoyancy, the greater the potential danger of a passenger becoming trapped in a submerged helicopter and unable to escape. If a survival suit, mandatory for such flights, fits well and is vented properly, trapped air will be minimised. However, on immersion in water, the air that is trapped inside the survival suit will be forced upwards. This is likely to escape from the suit's neck or wrist seals, and in the case of the 1000 series suit (Survitec Group) worn by UK offshore workers, through one-way valves fitted at the shoulder. Air escape on instantaneous immersion has been previously estimated to be complete in 10 s (Brooks 1988), although the quantity of air escaping was not assessed. The design of the suit, its tightness, location of air pockets inside the suit, together with the orientation of the body on immersion are all likely to have an influence on how readily air will be expelled on immersion. This escaping air can also lead to water ingress into the suit as the seal is broken (Coleshaw 2010), which reduces the insulation provided by the suit, depending on its extent and location (Power et al., 2016; Tipton 1997).

Empirical evidence and observations of diving strategy in Weddell seals of different fatness points to the energetic penalty of increased buoyancy for swimming below the water surface (Sato et al. 2003). The same physical principles of buoyancy are also likely to adversely affect humans in the same way, when they try to swim down from the water surface. Evidence from helicopter ditchings has identified survival suit buoyancy as a causative element in the inability to make a successful egress from a flooded cabin (Brooks and Rowe 1984). The inherent buoyancy of an insulated helicopter suit, together with the trapped air inside it was previously proposed to have a maximum of 178 N when its wearer had been totally submerged in a vertical orientation, although trained divers failed to escape at levels of buoyancy between 173 and 267 N (Brooks 1988). The additional buoyancy attributable to clothing was estimated to be 44-89 N in different assemblages, so in order to constrain total buoyancy to the proposed figure, the suit itself was required to have no more than 89 N of buoyancy. These preliminary figures were based on testing of only four individuals (Brooks and Potter, 1986), and were later revised downwards. Particularly in Eastern Canada where much of this work was carried out, but everywhere which has very cold water conditions, the challenge is to provide sufficient insulation without making the suit system excessively buoyant. In an experiment in a helicopter underwater escape training (HUET) facility with 12 participants, Brooks (1988) identified a suit system with inherent buoyancy of 155 N as the value at which some participants began to fail to escape, and concluded that 146 N does not prevent successful escape. Important observations during these experiments have added to our understanding of the issue. On unclipping the seatbelt, the legs would “float haphazardly” on inversion “which predisposed him / her to disorientation and difficulty with adopting a good position to make the escape”. Greater strength and reach were both highlighted as favourable attributes for successful escape, strength enabling greater stability, and longer reach envelopes optimising grip and leverage which would aid the egress manoeuvre. These observations are counterpoised against the logical advantage a smaller person would be anticipated to have, both in terms of buoyancy and also egress through a restricted opening. However, at present, it is unknown whether body size, shape or weight might influence buoyancy in offshore workers. Such a knowledge gap is important to fill, because of the direct implications for a range of factors including survival suit design, helicopter interior layout and helicopter underwater escape training. Indirectly, human factors relating to seating preference, comfort, and the morale of the workforce have the potential to be affected by this knowledge. Therefore the over-arching purpose of the study was to determine if a size-buoyancy relationship exists. The first objective was to measure the volume of air expelled as a function of water immersion in a small sample of varying body size. The second objective was to apply an algorithm which predicts air expulsion to calculate body density and buoyancy across a representative sample of the UK offshore workforce to predict buoyancy.

Method

A) Immersion study

A convenience sample was recruited comprising eight male volunteers aged 39.8 $\pm$ 12.6 y (mean $\pm$ SD). Their body size and shape differed appreciably, and body mass index (BMI; mass in kg divided by the square of stature in m) averaged 28.9 $\pm$ 6.4 $kg.m^{-2}$, and ranged from 22.0 – 39.9 $kg.m^{-2}$, equivalent to the 4^{th} - 99^{th} percentile of the offshore workforce respectively (Ledingham et al., 2015). These individuals were either participants in the validation work for the scanner study of offshore workers' size & shape, or were safety representatives for the UK offshore industry.

B) Offshore workforce

Male UK offshore workers aged 40.6 $\pm$ 10.7 y whose BMI averaged 28.3 $\pm$ 4.0 $kg.m^{-2}$ were recruited for the Size and Shape of Offshore Workers (SASOW) study (Ledingham et al. 2015), by quota sampling across seven weight categories (n = 588; 84 in each), to match the curve of most recent available weight data of the entire workforce of 45000 individuals . These categories in kg were as follows: <76.4; 76.5 - 82.4; 82.5 - 87.4; 87.5 - 91.4; 91.5 - 97.4; 97.5 - 104.4; >104.5. These categories were the optimal fit for the curve of the workforce weight data and matched almost perfectly. [Chi-square value = 11.7; 11 df, P=0.613]. The sample size constrained the 95%

confidence interval for the true workforce weight to 1.1 kg – a figure which could be expected with diurnal weight fluctuation.

Measurements

A)) Immersion study

Participants wore two layers of indoor clothing (T shirt and fleece) without shoes and were measured for body mass. After donning the appropriately-sized suit according to manufacturer's recommendations based on stature and chest girth, individuals performed a standard venting manoeuvre which involved squatting down and holding the neck seal open to release the trapped air, and re-sealing it before standing up. Each was scanned in a poolside room with adequate space (2.5 x 2.5 m) and precautions which included the uses of circuit breakers. Participants stood erect with the legs straight and arms by the sides, and were encouraged to adopt shallow breathing while wearing a full survival suit over their indoor clothing. The scan lasted 30–45 s and used an Artec L scanner (Artec Group, Luxembourg), after which participants were weighed using a portable digital scale (model 899, Seca, Hamburg, Germany). Scans were processed using Artec studio 9 software (Artec Group, Luxembourg), which involved registration, fusion, and where necessary, hole-filling and mesh simplification. The rendered object was then quantified for volume. The volunteer jumped from the pool side into the deep end of the pool, ensuring complete submersion was achieved, before exiting the pool up the steps (see figure 1), ensuring that no rapid or vigorous movement disturbed the wrist or neck seals. After approximately two minutes, when participants were dabbed dry using towels, they were re-scanned using the same procedure.

*** figure 1 near here ***

B) Offshore workforce

Participants were professional ‘core crew’ (generally working at least 100 days offshore per year), recruited via Oil & Gas UK and key stakeholders. Each was scanned wearing form-fitting shorts, and also in a full survival suit and lifejacket over their regular indoor clothing using the same scanning system and also weighed using the same portable digital scales, as part of a larger study of body dimensions (Ledingham et al. 2015) which informed space requirements in restricted width (Stewart et al. 2015a) and simulated helicopter window escape (Stewart et al. 2015b). Volumes obtained from scans, together with scale mass enable the calculation of density and combining this with an estimate of air expelled on immersion is thus useful in order to inform whether density, and consequently buoyant force is affected by body size, although these parameters would not be practicable to measure in a large sample. Measurements were acquired mostly at an Aberdeen heliport, in addition to Aberdeen-based operators' offices and a heliport in Norfolk which services the Southern North Sea sector. The study was approved by Robert Gordon University's Research Ethics Review Committee, and all participants gave written consent.

Theoretical basis

Archimedes' principle states that the buoyant force acting on a submerged object equals the weight of the water it displaces. If the water density equalled unity the weight of the water displaced (in kg) would be numerically similar to the volume of the body (in l). However, in a liquid whose density differs from unity, the force of the weight (the mass multiplied by the earth's gravity constant) is necessarily multiplied by the density. A completely submerged object exerts a buoyant force (N) according to the formula:

$$F_B = V.\rho.g$$

where V is the volume of the object, ρ is the density of the fluid, and g is the acceleration due to gravity, as summarised schematically in figure 2. In the current context, the volume of water displaced is predicted to be the measured dry volume minus the predicted volume loss on immersion. The density of sea water varies between about 1.02 and 1.03 $g.cm^{-3}$, and is affected by salinity, temperature and other variables in a complex system (see Wang, Dong and Munoz 2010 for a review). For the purpose of this paper, the body will be treated as a rigid object of uniform density, the density of the North Sea water will be assumed to be 1.027 $g.cm^{-3}$, and the earth's gravity constant, 9.8 $m.s^{-2}$. This force is opposed by the force of the weight of the suited individual (N) , as the product of the measured body mass m and the earth's gravity constant g. The net buoyant force (N) is given by the formula:

$$\text{Net buoyant force (N)} = (V.p.g) – (m.g)$$

*** figure 2 near here ***

Results

Physical characteristics of the eight participants of the immersion study are provided in table 1.

*** table 1 near here ***

On immersion, air escaped from the shoulder vents, and this reduced the post immersion volume. One participant's suit flooded due to a failed seal, and as a result the post-immersion volume was similar to that for pre-immersion, and as a result, his data were excluded from the analysis. The pre and post immersion volumes are depicted in figure 3.

*** figure 3 near here ***

Volume reduction after immersion as the dependent variable was better predicted by dry density (the weight of the participant in the suit plus rebreather, divided by the total volume, dry) than BMI or other variables, as illustrated in figure 4. Linear and power regression analyses were carried out using the volume of air expelled as the dependent variable and 'dry density' as the independent predictor. The following regressions were obtained:

Volume loss on immersion (l) = (-81.429 * dry density)+ 77.008

R^2 (adj) = 0.56; SEE = 3.48; $P< 0.05$

Volume loss on immersion (l) = 4.1077* dry density$^{-4.531}$

R^2 (adj) = 0.63; SEE = 0.22; $P< 0.05$

*** figure 4 near here ***

After the volume loss, predicted from both linear and power functions, was subtracted from the dry volume, the resultant buoyant force in sea water was calculated. Mean predicted buoyant forces were 264 $\pm$ 46 and 232 $\pm$ 60 N using the linear and power functions respectively. Corresponding values for pool water are 232 $\pm$ 43 and 201 $\pm$ 55 N. For both functions, the heaviest individuals were predicted to have the highest buoyant force, and the lightest the lowest ($P<0.01$ for linear $P<0.001$ for power functions for all non-adjacent weight categories, after Bonferroni correction) as depicted in figure 5. Post hoc Tukey test revealed four homogeneous subsets for buoyant force across the seven weight categories for the linear function, whereas the power function partitioned each weight category into a different subset.

*** figure 5 near here ***

Due to the nature of the mathematical adjustments, a greater difference was made by the power algorithm to individuals near the extremes of the weight range, as depicted in figure 6.

*** figure 6 near here ***

Discussion

Predicted buoyant force in offshore workers calculated from volume loss on immersion exhibits a gradient by body weight and is smallest in the lightest individuals and greatest in the heaviest. Contrary to what might be anticipated from measured 'dry density'(which ranged from 0.63 $g.cc^{-3}$ in the lightest to 0.74 $g.cc^{-3}$ in the heaviest, and was different between all non-adjacent weight categories groups, $P<0.001$, after Bonferroni adjustment), this finding is explained by proportionately more air being expelled from the suits of lighter individuals on immersion, which more than compensates for their lower dry density. Lighter individuals may wear suits which, despite being sized appropriately, provide a less tight fit. As a result, more loose material which may crease and fold has the potential to trap air, even after the dry venting manoeuvre. Heavier individuals may have lower body density than lighter individuals due to increased fatness, but further measures would be required to confirm this. However, even if so, when wearing clothing and survival suit, heavier workers have less trapped air. Overall buoyancy is influenced to a much greater extent by lung volume and trapped air than body fatness. When underwater weighing to determine body fatness, as little as 100 ml added to residual lung volume increases predicted % fat by 0.7% (Going, 2005), so even if evidence exists that heavier workers may have greater fat than their lighter counterparts, its influence on buoyancy is unlikely to be pivotal.

The mean predicted buoyant forces of 264 N (linear) and 232 N (power) represent a reduction in buoyancy of 217 N and 249 N from the equivalent calculation based on dry density. The figure of 481 N which is the theoretical buoyancy in the absence of any air escaping from a typical UK offshore worker's suit does not vary between weight categories (P=0.48), and highlights just how much air remains in the suit after venting, and the fundamental contribution of suit design to lessening buoyancy on immersion. It is not apparent from extant literature what maximum buoyancy could be overcome to swim beneath the water surface without mechanical advantage, however, the mean figure may reflect that suits were either sub-optimally fitted, venting was poorly executed or air re-entered the suit after venting. This may not be a concern when immersion is vertical, the shoulder valves perform as designed, and expel air effectively. However, excess air could conceivably become trapped by constriction or body orientation and not be forced out of the valves. Under these circumstances, it would be very difficult to overcome the buoyant force unless mechanical advantage was possible allowing individuals to pull themselves below the water surface.

Helicopter survival suit design criteria need to balance the required insulation with the consequent buoyancy which may impede underwater escape in an emergency (Coleshaw 2010). The fact that the heaviest individuals may have the greatest buoyant force, as shown by our data, is countered by the likelihood that such individuals are likely to be physically bigger, with greater reach and better leverage for pulling the body down through the water in order to make an escape. Inherent buoyancy in clothing is likely to be highly variable according to the materials and fit, however the estimation of 45-89 N detailed in Brooks (1988) may appear conservative. Although the density of swimming pool water may be 3% less than that of sea water, this may have reduced slightly the hydrostatic force and underestimated the volume loss on immersion in seawater. However, the strict protocol, together with previous literature on the time for air expulsion to be complete suggests this is not a large source of error. Participants did not wear either a lifejacket or an emergency breathing system over the survival suit. Undoubtedly, these would influence air movement within the suit, expulsion and buoyancy, but lifejackets were not worn in the current study, mainly because professional requirements and practice vary in different parts of the world, so this addition would limit the study's generalizability.

The survival suits appeared to perform their function extremely well, whereby air was expelled through shoulder vents, the seals remained intact, and there was virtually no dampening of clothing around them. However, given the enormous range of theoretical buoyant force prior to immersion, the importance of adequate venting of suits is critical. The question of which algorithm should be applied to calculate buoyancy needs careful consideration. Both predictions paint a similar picture of greater predicted buoyancy in larger individuals, although the extent of this varies between them, especially at the lighter extremes of body weight. The linear algorithm has poorer explained variance and wider error, yet the power algorithm appears to lack plausibility below about 75 kg, because the inherent buoyancy of the suit plus clothing would be overwhelmed by the body density.

Further research is clearly warranted to augment this study's findings if the accuracy of the prediction is to be improved. While this could confirm whether a linear or power function should be applied to predict buoyancy, it could usefully contribute in a range of applications. Venting practice varies considerably worldwide, because not all suits have similar neck seals, some still using zips which would need to be sealed immediately prior to a landing on water. In reality, air escape from the suit may be highly variable between individuals of similar weight but different shape, and there may be scope for further research of venting efficacy, especially in larger individuals. Further study could also consider the effect of different clothing assemblages on buoyancy, which varies worldwide according to sea temperatures. Experimental work has shown buoyancy is elevated due to trapped air in winter clothing assemblages compared to those of spring/autumn and summer (Barwood et al., 2011). However, seasonal clothing policy adjustments for offshore workers travelling by helicopter may have consequences for buoyancy which may not be widely appreciated by the global offshore workforce because practices for helicopter underwater escape training may not routinely involve full survival suit specifications. Rather, it may involve suits designed for warm water training which lack a thermal liner, and are appropriately designed for very high usage, abrasion resistance and rapid drying. While water temperature has a small effect, the consequence of clothing policy as a result of sea temperature has a large one, added to which variable salinity in different parts of the world can also contribute variation (Wang et al., 2010). However, due to the costs of replicating an authentic sea environment to represent different geographical areas, it is likely that such work will necessarily proceed on a more local level, where both climatic and regulatory processes prevail.

While this study has employed a predictive technique based on only seven individuals, it has highlighted a previously unknown and important concern regarding the relationship between body size and air loss on immersion, and underscores the importance of venting for offshore workers. This is materially important in safety terms and how buoyancy impacts underwater egress should be the focus of further research, because it is possible that some individuals may exceed the safe limit that must be overcome to enable escape from a submerged helicopter.

Funding: This work was supported by a Knowledge Transfer Partnership grant no KTP008973 between Robert Gordon University and UK Offshore Oil and Gas Industry Association Ltd. In-kind support was received from Survival One (Survitec) Aberdeen, who provided survival suits for the study.

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Figure 1. L: scanning prior to immersion; centre: vertical water entry; R: exiting the pool after immersion showing the suit ‘clinging to the body’ after air expulsion

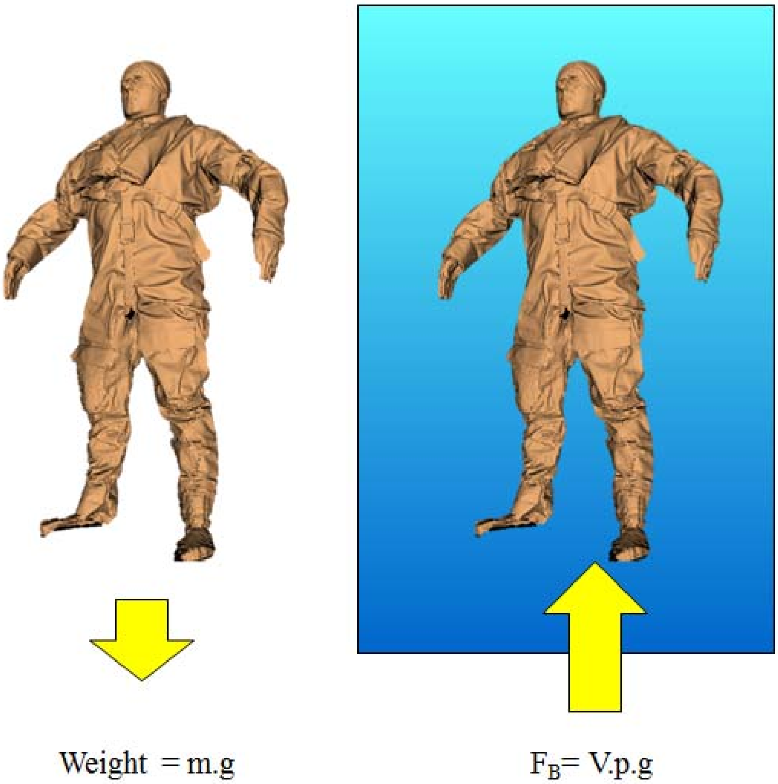

Figure 2. Forces acting on an immersed object. L: in air; R: in water

Table 1. Physical Characteristics of participants

	Age (y)	Stature (cm)	Mass (kg)	Chest girth (cm)	Body Mass Index (kg.m^{-2})
Mean	39.8	177.5	90.0	107.2	28.6
SD	12.6	4.7	17.1	13.1	6.0
Min	25.7	170.0	68.3	86.5	22.0
Max	57.1	186.0	115.5	121.3	40.0

n=8

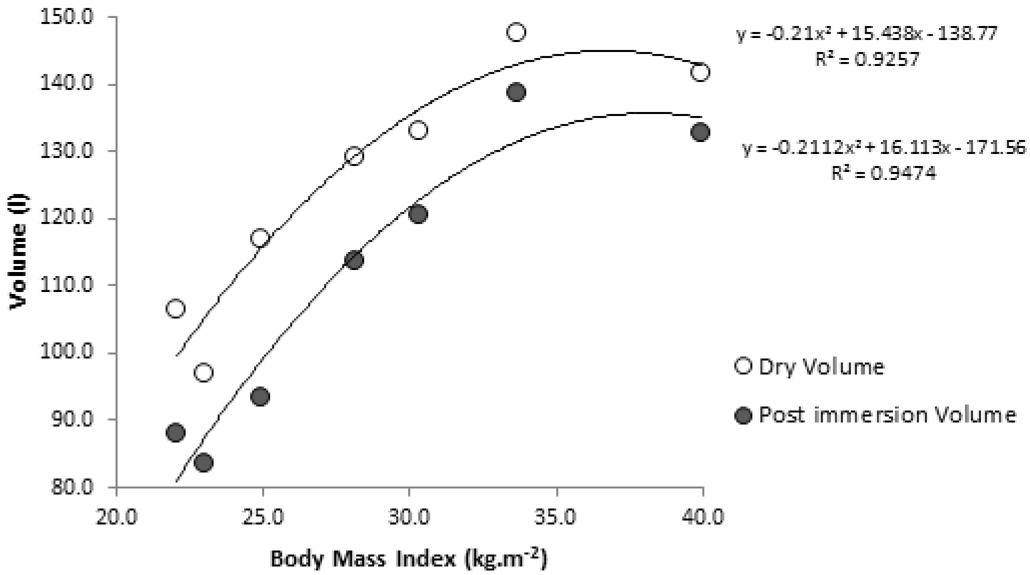

Figure 3. Pre-immersion (‘dry’) and post-immersion volumes (n=7).

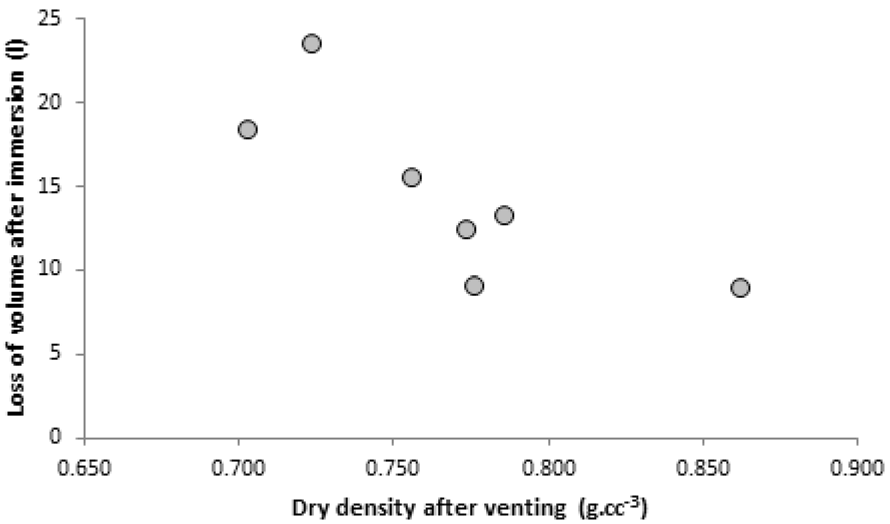

Figure 4. Volume loss on immersion plotted against dry density (n=7).

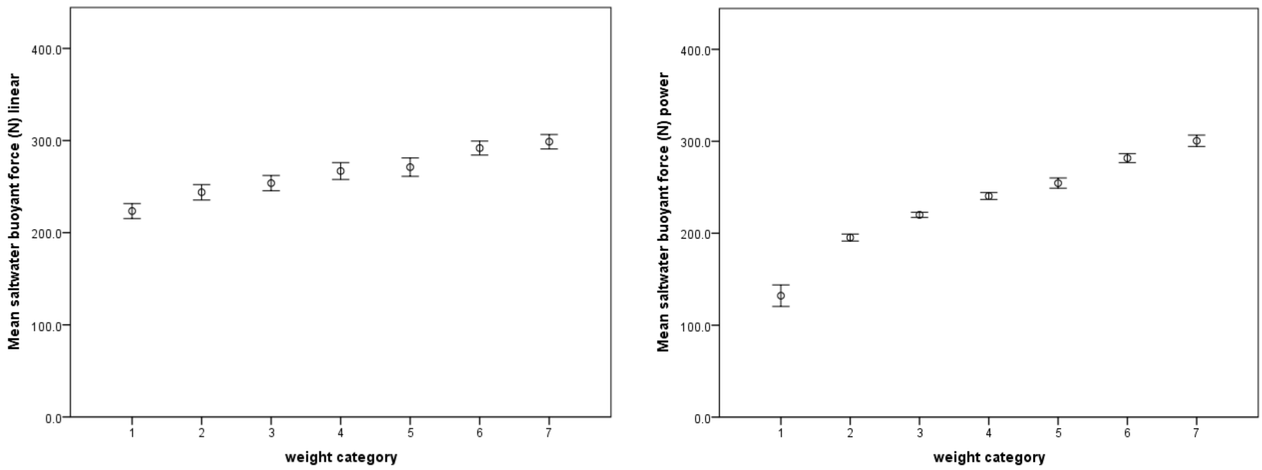

Figure 5. Predicted salt water buoyancy for weight categories using linear (L) and power (R) functions. Weight category 1:<76.4 kg; 2: 76.5-82.4 kg; 3: 82.5-87.4 kg; 4: 87.5-91.4 kg; 5: 91.5-97.4 kg ; 6: 97.5-104.4 kg; 7: >104.5 kg. Error bars represent 95% CI. $P<0.01$ for linear $P<0.001$ for power functions for all non-adjacent weight categories, after Bonferroni correction

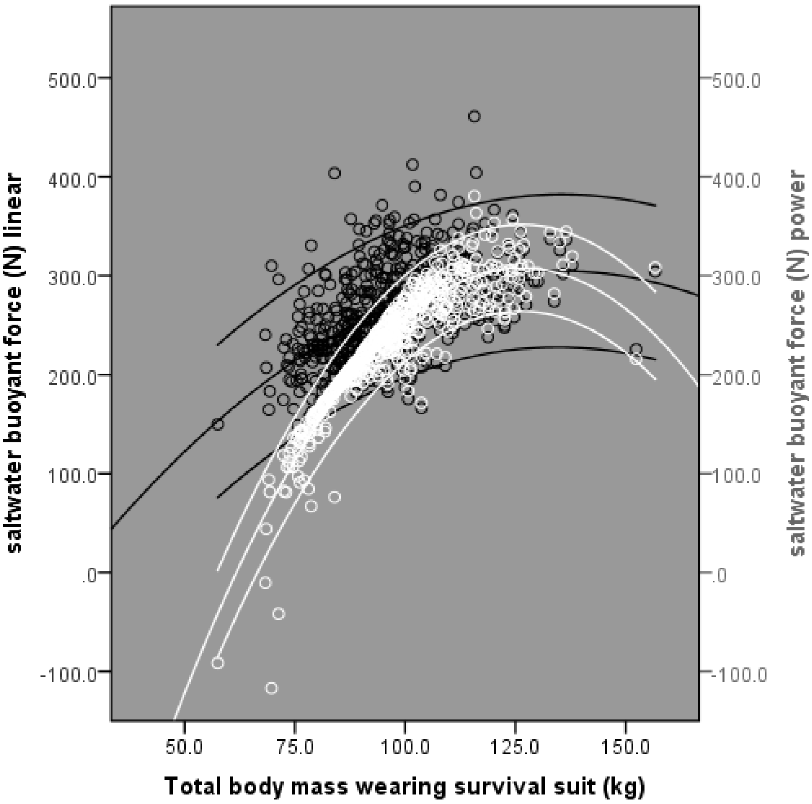

Figure 6. Predicted salt water buoyancy, plotted against total mass. Y axis (L) refers to linear prediction of saltwater buoyancy, and (R) refers to a power prediction of the same (both in Newtons). Black circles refer to linear calculation; white circles refer to power calculation. Lines refer to 95% CI around best fitting curve.