

Reproducibility of Body Volume Assessments in Survival Clothing in Fixed and Portable Scanning Systems

Robert J. LEDINGHAM^a, Alan M. NEVILL^b, Arthur D. STEWART^a

^a Robert Gordon University, Institute of Health and Welfare Research, Aberdeen, UK;

^b University of Wolverhampton, School of Sport, Performing Arts and Leisure, Walsall, UK

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Abstract

The recent development of portable 3D scanning systems for industries such as animation and museum artefact digitisation have considerable potential for applications involving human body measurement. However, this requires a system for validation of measurements against a criterion, which this study aimed to provide. Forty four adult males were scanned in duplicate in both a fixed Hamamatsu and portable Artec L scanning systems in two postures and two different clothing assemblages. Following inspection of all scans, complete data for duplicate scans of 38 participants were available for the study. Both scanners demonstrated good precision, however significant differences in body volume prevailed for both egress and scanner postures in form-fitting clothing and the scanner posture in survival suit scans, with the Hamamatsu providing greater volumes than the Artec system (by 2.7, 2.8 and 2.1 litres respectively). Regression analysis indicated the results from the portable scanner explained between 96 and 98% of the variability in the results from the fixed scanner. The biases in body volume probably relate to different software approaches to its calculation, and a possible interaction with posture and clothing. Validation of the Artec against the Hamamatsu system provides valuable information for its use in field and industrial settings.

Key Words: 3D scanning; body volume; posture; survival clothing

1. Introduction

Body volume is an important consideration in health and design settings across a range of industries. Body volume can affect a range of functional parameters such as physical space requirements, locomotion patterns and heat exchange. Larger people not only require more physical clearance, but may move in a gait which has greater lateral displacement, thereby exacerbating space needs. Such individuals also have lower surface area-to-volume ratios, and consequently a slower rate of heat gain and loss, which can both protect and threaten health in different environments. Surveys which capture body size data are required to model such factors, and this involves measuring the body in form-fitting clothing.

In physically demanding work across a range of industries, size-related factors profoundly influence work capability and are important safety considerations, especially in restricted space environments. For workers in the offshore oil industry, specialist clothing, designed to facilitate survival in cold water immersion is required for helicopter travel to installations in the North Sea. While the requirements for insulation vary worldwide according to the ambient water temperatures, in the UK energy sector, standardised survival suits are designed to be worn over three layers of clothing. This clothing is accommodated within the ease-allowance of the suit which is 'vented' after donning in order to reduce trapped air which would provide excessive buoyancy and hence be dangerous in the event of sudden water immersion. When wearing the suit, even after venting, body volume measures remain substantially greater than with form-fitting clothing, although this size step change is not quantified in extant data. In addition, such limited data which do exist on the size of UK offshore workers are from anthropometric measurements acquired in the mid-1980s. As a result of demographic change, and ageing workforce and the possibility of the influence of global obesity, little is known of the body size of the 45,000 employees who currently work in the UK offshore sector. As a result, a range of issues including suit sizing and space considerations when wearing suits have not been addressed with a comprehensive approach.

Three dimensional scanning (3DS) technology has been developed for measuring body shape and volume using fixed scanners. These have been used to execute a large size survey in the UK, where they were mounted inside a mobile laboratory and measured a large sample from different geographical regions [1]. However, a laboratory-based approach may not be effective in highly selected samples, because the infrastructure and development costs are high. More recently, with the advent of portable 3DS, employees may be scanned in their place of work without the requirement

to visit research laboratory facilities. However, portable scanners have been only recently available, and with applications in the animations industry and for digitising museum artefacts, limited development has been undertaken to extract measurement data in living humans. If they can be validated for measuring people, a range of scanning surveys which would hitherto have been impossible, would therefore be feasible. These would have the potential to characterise body types across a range of professions, with applications in protective clothing, body armour and transportation. However, this assumes the portable scanner can be calibrated for use in the field, with measurement errors quantified.

The aim of this study is therefore to conduct a validation of a portable scanning system, which will be met by the following objectives:

- To determine the agreement between fixed and portable scanning systems for measuring body volume;
- To quantify the precision errors according to scanner type, body posture and between wearing form-fitting clothing and a survival suit.

2. Methods

Forty four healthy males aged 31.2 ± 12.2 y with body mass index 26.2 ± 4.4 kg.m⁻² were recruited from the University and local community. All participants were measured for stature and mass, and provided with a survival suit (500 series Helicopter passenger survival suit (Survitec group, Birkenhead, UK) according to the manufacturer's size guideline, and illustrated in figure 1.



Figure 1. A study volunteer wearing survival suit and re-breather.



Figure 2. L: Hamamatsu BLS Scanner R: Artec L portable scanner.

After screening for photo-sensitive epilepsy, each participant was scanned using a Hamamatsu BLS 9036-02 fixed scanner (Hamamatsu Photonics, Japan) and an Artec L portable scanner (Artec-Group, Luxembourg) as illustrated in figure 2. Scanning acquisition times were ~ 10 s and ~ 60 s respectively. Each participant was measured in duplicate scans in different postures: “egress” (with the hands by the side) and “scanner” (with arms and legs abducted), wearing form-fitting lycra clothing, and a survival suit worn over regular indoor clothing as illustrated in figure 3. The 16 scans per participant were completed within the same measurement appointment. For the Hamamatsu scanner, light colours are essential, and the appropriate sized survival suit was covered in talc in order for its shape to be detected. For the Artec scanner, it was necessary to stabilise the arms with the use of adjustable walking poles which were located in wooden blocks on the floor. System software enabled the poles to be erased before analysis. All scans were made in duplicate, and completed within the same measuring session lasting approximately one hour. Participants provided informed consent, and the study received institutional ethics approval.

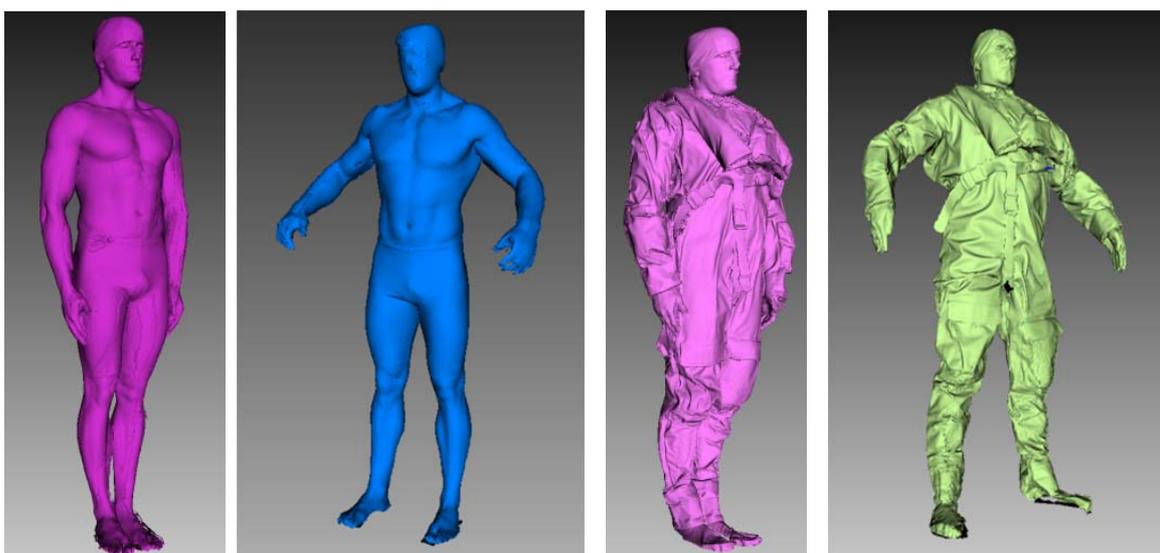


Figure 3. L to R: Volunteers in form-fitting clothing in egress and scanner positions; survival suit egress and scanner positions.

Scans were analysed according to manufacturers’ software recommendations, and each resulting scan was scrutinised visually to check for missing data or movement. Complete data were available for 38 individuals. Analysis of the data included technical error of measurement (TEM) for precision, Bland and Altman analysis for agreement and regression analysis for benchmarking. The level of statistical significance was set at $P < 0.05$.

3. Results

TEM expressed as a percentage of absolute volume was used to quantify precision error of repeated scans is illustrated in table 1. Both scanners demonstrated good precision. The Hamamatsu scanner had better precision in form-fitting scans, while the Artec scanner was better with survival suit scans.

Table 1. %TEM values for volumetric measures.

| posture | Form fitting clothing | | Survival Suit | |
|---------|-----------------------|-------|---------------|-------|
| | Hamamatsu | Artec | Hamamatsu | Artec |
| Egress | 0.79 | 1.28 | 1.54 | 1.03 |
| scanner | 0.85 | 1.48 | 1.03 | 0.97 |

n = 38

Mean volumes for each scanner, position and clothing illustrated in table 2.

Table 2. Mean and standard deviation of body volumes (l) by scanner, posture and clothing.

| | Hamamatsu | Artec | 95% CI of difference | %CV | P |
|-----------------------|--------------|----------------|----------------------|------|----------|
| Form-fitting egress | 86.9 ± 15.3 | 84.2 ± 14.2 | -3.497, -1.992 | 2.68 | < 0.0001 |
| Form-fitting scanner | 87.6 ± 15.2 | 84.8 ± 14.4 | -3.533, -2.003 | 2.70 | < 0.0001 |
| Survival suit egress | 142.7 ± 15.8 | 142.3.0 ± 15.0 | -1.269, 0.478 | 1.86 | 0.365 |
| Survival suit scanner | 144.3 ± 15.7 | 142.2 ± 15.5 | -3.151, -1.203 | 2.07 | < 0.0001 |

n = 38; paired t-test, 2-tailed; %CV : SD of the difference divided by the mean, expressed as a percentage

Regression analysis, with the portable Artec scanner predicting the volumes derived by the fixed Hamamatsu scanner are summarised in table 3.

Table 3. Regression analysis for body volume using the Hamamatsu scanner volume as the dependent variable, and the Artec scanner as the independent variable.

| | B Coefficient | Constant | R ² | SEE | P |
|-----------------------|---------------|----------|----------------|------|----------|
| Form-fitting egress | 1.066 | -2.823 | 0.981 | 2.11 | < 0.0001 |
| Form-fitting scanner | 1.044 | -0.927 | 0.978 | 2.27 | < 0.0001 |
| Survival suit egress | 1.038 | -4.972 | 0.972 | 2.63 | < 0.0001 |
| Survival suit scanner | 0.999 | 2.331 | 0.964 | 3.00 | < 0.0001 |

n=38

4. Discussion

Reproducibility of the scanners for assessing volume compares favourably with that for anthropometric measures of distance, which would be required to be < 2% for girths, lengths and breadths [2]. As anticipated, poorer precision prevailed for form-fitting scans acquired by the portable scanner due to its longer acquisition time (~60 s for the whole body) relative to the fixed scanner (~10 s) which increases the scope for breathing artefacts and postural movements. However, the reverse was true for the survival suit scans, where the portable scanner was more precise. The reasons are not entirely clear. This may be because the Hamamatsu scanning system is designed for measuring the skin surface or light coloured clothing, and neither the dark clothing nor the reflective components of the survival suit. These challenges to the laser scanning system may outweigh the benefits of a faster scan time. Nevertheless, the acceptable reproducibility underscores that this tool can be adapted for these materials with the use of talc.

Volumetric differences between the scanners were not significant with participants wearing the survival suit in the egress position. Why this occurred in the egress position while the mean difference of 2.1 litres prevailed in the scanner position is not entirely clear. It is possible that the hole-filling algorithms with touching body segments behave differently. In addition, the Hamamatsu software required to measure individuals in the egress position as an object, rather than a body, because the primary landmarks required for segmentation could not be placed without the legs and arms abducted. However, the mean volume difference of 2.7 litres in form-fitting egress scans between the scanner types suggests a difference in the analytical approaches used by each. Collectively, these observations point to a possible interaction of posture, clothing properties and data generation within software.

Early work comparing volumes between 3DS and underwater weighing in 22 adults found a bias of 0.52, but limits of agreement of 2.4 litres [3]. The authors used an early model Hamamatsu Bodyline Scanner and explained the observed volume difference between methods by the inability to identify precise lung volumes at the time of scanning. These can make a substantial impact (~ 5 litres) on total body volume in a typical adult. In addition to this, there may be large individual differences between the measured and predicted lung volumes used in underwater weighing and 3DS respectively. The authors converted volumes to % fat and highlighted that the lack of agreement between techniques could not be attributed to a lack of precision of methods.

Subsequently, Wang and colleagues used a later model scanner (BLS 9036-02, as in the current study) and underwater weighing (with lung volume measured simultaneously) for volume and % fat prediction in 63 adults [4]. The 3D measures were slightly but significantly greater than those using manual anthropometry or densitometry-derived volume (mean difference 0.4 litres). However their scanning protocol required the participants to maintain a posture under full exhalation for ~ 10 s,

which may affect shape and volume, and induce movement during the scan. Despite the slight difference in body volume measures between densitometry and 3D scanning, when converted into a % fat the differences were no longer significant. The authors did conclude that accurate volume measures were possible using 3D scanning if appropriate clothing was worn and the protocol was adhered to.

Taken together, these two previous studies suggest that the Hamamatsu scanning system may overestimate the true volume, but typically only by 0.4-0.5 L. This does not explain the magnitude of the difference from the Artec scanner in the present study. These observed differences may reflect the way each device acquires data, and assimilates it into a 3D model. In the fixed scanner, the horizontal array beam assesses a shape perimeter in a series of slices which are summed to produce volume. The portable scanner's ability to look above and below the horizontal, enables a greater detail to be detected. Because the Artec scanner acquires several times more data points to describe whole body shape, when the scans are rendered into a polygon mesh, the images appear much sharper and have a much larger file size. Additionally, its hole-filling algorithms appear to be more comprehensive in its proprietary software, Artec studio 9. A coarser rendering such as in the Hamamatsu system's Body Line Manager software whereby the polygon has fewer data points to base itself on might conceivably generate a larger volume, because the body is 'scanned from the outside in'. However this does not explain how the Artec scanning system might underestimate true volume, which could be inferred if underwater weighing is assumed to be accurate in previous studies, and the difference extrapolated to the current sample. Neither does it explain the similarity between survival suit scans in the scanner and egress positions with the portable scanner (mean difference 0.18 litres; $P=0.535$) as contrasted with the fixed scanner (mean difference 1.6 litres, $P<0.001$). However, this study does quantify the mean calibration error (mean differences divided by mean value, expressed as a percentage) of -2.05% for the Artec L against the Hamamatsu, and provide regression equations which facilitate its use in the field.

It is possible to learn something from the outlier data which were discarded from the analysis. The Hamamatsu's body line manager software appeared to miss data points on some individuals, such that entire sections of the arm or thorax were missing. Ambient light or a lack of talc on these areas of the survival suit may have been responsible. Hirsutism in one participant may have exacerbated volume differences between scanners. Body movement was unlikely to have influenced the volumes in such a rapid acquisition time.

5. Conclusion

Body volume measurements remain useful in a variety of contexts, including the quantification of body fatness, and the design of work space. While further research with other modalities such as underwater weighing or air displacement plethysmography may further enhance the calibration of the Artec L scanner, validation against the Hamamatsu system shows a mean calibration error of -2.05%. This low error, together with the regression equations provided will facilitate its future use in a range of field and industrial settings.

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