The use of consumer depth cameras for 3D surface imaging of people with obesity: a feasibility study

Wheat, J.S.[1], Clarkson, S.[2], Flint, S.W.[3], Simpson, C.[4], Broom, D.R.[4]
[1] Centre for Sports Engineering Research, Health and Wellbeing Research Institute, Sheffield Hallam University, United Kingdom.
[2] Institute of Medical and Biological Engineering, School of Mechanical Engineering, University of Leeds, Leeds, United Kingdom.
[3] School of Sport, Leeds Beckett University, Fairfax Hall, Headingley Campus, Leeds, United Kingdom.
[4] Academy of Sport and Physical Activity, Sheffield Hallam University, United Kingdom.

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Corresponding author:
Dr Jonathan Wheat
Centre for Sports Engineering Research
Sheffield Hallam University
11 Broomgrove Road,
Sheffield,
S10 2LX,
UK
T: 0044 114 2254330
F: 0044 114 2254356
E: j.wheat@shu.ac.uk

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Abstract

Objective: Three dimensional (3D) surface imaging is a viable alternative to traditional body morphology measures, but the feasibility of using this technique with people with obesity has not been fully established. Therefore, the aim of this study was to investigate the validity, repeatability and acceptability of a consumer depth camera 3D surface imaging system in imaging people with obesity.

Methods: The concurrent validity of the depth camera based system was investigated by comparing measures of mid-trunk volume to a gold-standard. The repeatability and acceptability of the depth camera system was assessed in people with obesity at a clinic.

Results: There was evidence of a fixed systematic difference between the depth camera system and the gold standard but excellent correlation between volume estimates (r^2=0.997), with little evidence of proportional bias. The depth camera system was highly repeatable - low typical error (0.192 L), high intraclass correlation coefficient (>0.999) and low technical error of measurement (0.64%). Depth camera based 3D surface imaging was also acceptable to people with obesity.

Conclusion: It is feasible (valid, repeatable and acceptable) to use a low cost, flexible 3D surface imaging system to monitor the body size and shape of people with obesity in a clinical setting.

Keywords: 3D Surface imaging; body morphology measurements; weight management

Introduction

The measurement of obesity and body morphology continues to be important to clinicians, researchers and the general population. Current methods for tracking participant progress in weight management programmes are simple (e.g. weighing scales, tape-based measurements) [1]. Medical imaging techniques - including Dual-energy X-ray absorptiometry [2], Magnetic Resonance Imaging [3-5] and Computed Tomography [6] - have been used to make more sophisticated measurements. However, these techniques are not in widespread use because they are complex, expensive, hard to access, irradiating (in some cases), and require skilled operators.

Three dimensional (3D) surface imaging is a viable alternative for monitoring body morphology [7]. These non-contact, non-irradiating, light-based systems capture 3D models of the body surface topography. Three dimensional surface imaging presents several benefits over traditional manual measurements made with a tape measure: 1) it is fast, ranging from ~1.5 ms to ~15 s, 2) data can be archived, 3) models can be overlaid and 4) complex measures such as volume can be computed [8]. Moreover, it is less invasive than manual measurement and requires less contact time [9]. Finally, 3D surface imaging systems are likely to reduce inaccuracies [10] inherent with current manual techniques such as skin depression and soft tissue artefact [11], which are likely further exaggerated in people with obesity.

Three dimensional surface imaging systems can be used to acquire simple 1D measures, such as waist, hip and thigh girth. They have been demonstrated to show good agreement with manual measurements [12] and provide effective indication of the risk of several medical conditions [13-14]. However, more complex anthropometrics can be obtained which have been used to estimate visceral adipose tissue [15] and proportions of subcutaneous and visceral fat in the abdomen [16]. As such, these systems offer great potential for monitoring and evaluating people with obesity but their widespread use has been limited due to complexity, availability and cost.

Consumer depth cameras - e.g. Microsoft Kinect - offer the possibility of performing 3D surface imaging at relatively low cost and several systems leveraging this technology are now available, such as TC2 KX-16 (Cary, NC, USA) and Fit3D Proscanner (Redwood City, CA, USA). Recent studies have demonstrated that these systems can provide accurate, automated anthropometrics [17-18] but are expensive - ~£7,000-£15,000. An individual depth camera is only ~£150 so our group has developed calibration and camera correspondence algorithms that allow multiple off-the-shelf depth cameras to be combined to produce flexible and scalable 3D surface imaging systems [19-23]. This offers the possibility of obtaining accurate estimates of body morphology, conveniently and at very low cost. Wheat et al. [19] established that an early iteration of the approach could be used to measure the volume of a mannequin trunk, showing good agreement with a high resolution non-contact laser scanner (Modelmaker D100, Metris, Leuven, Belgium). In subsequent studies, we have demonstrated that our approach provides repeatable and accurate estimates of the girth and volume of inanimate objects, machined to represent human body segments [20]. The approach produced clinically acceptable agreement in the measurement of mammometric parameters used for planning and evaluating breast reconstruction surgery [22]. Further, good agreement has been demonstrated with manual techniques and a gold standard 3D surface imaging system (3DMD, Altlanta, GA, USA) for trunk [21] and thigh [23] volume, respectively, in normal weight participants.

The acceptability of 3D surface imaging to patients is another important feasibility consideration, but this has received little attention in the literature. Wells et al. [8] reported 3D surface imaging to be acceptable to children aged 5-11 years, with only 2.6% of those invited to participate declining. However, the rate of acceptance of invites to participate is a crude measure of acceptability, with more work required to explore this further, in adults as well as children. Moreover, Wells et al. [8] used an expensive, commercial 3D surface imaging system, with no information about the acceptability of systems based on consumer depth cameras.

The aim of this study was to investigate the feasibility of using low-cost depth camera 3D surface imaging with people with obesity. We sought to establish the validity and repeatability of the technique in the measurement of mid-trunk volume. Acceptability of the technique to participants attending a local tier 3 weight management service was also explored.

Methods

The study had two linked experiments. The repeatability of the technique was assessed in a sample of people with obesity at a local obesity clinic. Data collection at the clinic allowed the feasibility of field-based testing to be explored, together with the acceptability of the technique to participants However, it was not possible to investigate the validity of the technique in this environment, as no gold standard measurement system was available. Instead, a validity experiment was conducted in the Morphology Laboratory on University campus, with a suitable gold-standard. The depth camera 3D surface imaging system was common to both parts of this study. Details of this system are provided in the next section, followed by methods specific to both experiments.

Depth camera-based 3D surface imaging system

Setup

The system comprised four[a] depth cameras (Microsoft Kinect version 1, Microsoft, Redmond, WA, USA) mounted on a frame (protocol one) or tripods (protocol two) - see Figure 1. The depth cameras were connected to a single, standard personal computer. Our own software (KinanthroScan, Sheffield Hallam University, UK) interfaced with the depth cameras. To avoid interference, data were collected sequentially from each camera. In total, approximately 900 ms were required to collect all 3D point cloud data (a collection of 3D points). Point clouds from each depth camera required alignment to produce a complete 3D image of the mid-trunk. To achieve this, depth camera correspondence matrices were defined using a two-step calibration process which we have described in detail elsewhere [23]. The calibration takes approximately 9 minutes to complete and it was performed at the start of each data collection session, and repeated between each participant.

**** insert figure 1 near here ****

3D surface image acquisition protocol

Participants wore tight fitting clothing or nothing on their upper bodies. Before data collection, blue circular stickers (radius = 5 mm) were attached to the skin at the location of the left and right anterior superior illiac spine, sacrum, left and right nipple, and over the thoracic spine at the height of the nipple - approximately the tenth thoracic vertebra. During collection, participants were asked to lightly touch supports with their fingertips, as this support has been shown to reduce postural sway [27]. To eliminate the effects of breathing, participants were asked to pause their breathing (at end-tidal expiration) for the duration of the acquisition [9].

3D surface image analysis

All post-processing was performed using KinanthroScan. A single operator manually digitised the six anatomical markers, which were used to create inferior and superior segmentation planes (Figure 2a), defining the mid-trunk segment. We focussed on this region of the trunk as large variations were expected in people with obesity, with an asymmetric, eccentric shape, that is particularly difficult to model. The region was divided into 2 mm sections in the inferior to superior direction. All points in a section were projected onto a plane - passing through the section's centre - creating a 2D topological representation of the participant's body (Figure 2b). A cubic smoothing spline ($\rho = 0.79$) was fitted to these 2D points [28], creating a smooth collection of points defining the surface of the trunk in each

[a] Four cameras were used in this study (the minimum required to estimate mid-trunk volume), but the calibration and correspondence algorithms are scalable such that more cameras could be used if required.

section (Figure 2b). An implementation of discrete Green's equations was then used to calculate the volume of the mid-trunk across all sections [29].

**** insert figure 2 near here ****

Experiment one: Validity

Participants

It was not feasible for a large number of people with obesity to visit the laboratory. Also, many participants were too large to fit into the maximum sized measurement volume of a gold standard system achievable in the lab. Therefore, people without obesity were recruited for the lab-based validity experiment. Fourteen young, healthy participants volunteered to participate. Following institutional ethical approval and after being offered the opportunity to ask questions, participants provided written informed consent before data collection.

Procedure

Two 3D surface imaging systems were used in this experiment; the depth camera based system and 3DMD (3DMD LLC, Atlanta, GA, USA) which we considered to be 'gold standard'. The depth camera system was set up as described above and positioned within the 3DMD system (Figure 1). Set up of the 3DMD system was in accordance with the manufacturer's guidelines and data collection was triggered manually for each system. Entirely concurrent collection was not possible because of potential for interference between each system's structured light patterns. As such, data were collected consecutively, resulting in a total time of approximately 2 seconds. Data were collected and analysed using the protocol and methods described above. For the 3DMD data, anatomical markers were digitised using KinanthroScan and mid-trunk volume was calculated using a proprietary algorithm in Geomagic Studio (Three D Systems, Rock Hill, SC, USA)[b] - using inferior and superior segmentation planes defined in the same manner as for the depth camera system.

Statistical analysis

Agreement between the depth camera and 3DMD estimates of mid-trunk volume was assessed using several, complementary statistical measures. The degree to which differences between the measurement systems were systematic or random was explored using Limits of Agreement [30]. This was

[b] Mid-trunk volume data from the 3DMD system were also calculated using the algorithms built into Kinathroscan – the difference was minimal (0.19 ± 0.42 %). We chose to present 3DMD volume data calculated through Geomagic Studio to ensure the data were analysed in a gold standard manner, in addition to being collected using a gold standard system.

supplemented with paired samples *t*-tests to establish whether systematic differences were statistically significant. Finally, Least Products Regression [31] was used to delineate fixed and proportional systematic bias.

Experiment two: Repeatability, feasibility and acceptability

Participants

Following institutional ethical approval, 61 participants (Body Mass Index (BMI) = 40.4 ± 6.1 kg/m^2) enrolled on a weight loss programme at a local tier 3 weight management service volunteered to participate after receiving study information at the end of an existing consultation. Inclusion criteria required participants to be aged ≥ 18 years, have a BMI >30 kg/m^2 and able to stand unaided. Participants provided written informed consent and were given the opportunity to become accustomed to the data collection protocol.

Procedure

Three 3D surface images were collected, separated by approximately one minute. Data were collected and analysed as described previously. Acceptability was assessed using a questionnaire that was developed for the study because, to the authors' knowledge, no reliable and valid questionnaire has been published. The questionnaire contained items with Likert scale responses (1. strongly disagree, 2. disagree, 3. neither agree or disagree, 4. agree and 5. strongly agree). In addition, participants were asked to identify their preference for either 3D imaging or tape measurement and they were provided space to explain their responses or provide further comments.

Statistical analysis

Similar to validity, repeatability was assessed using multiple complementary techniques. Typical error was calculated for each pair of trials to identify presence of order bias. Relative accuracy was quantified by calculating intraclass correlation coefficients (ICC 2,1 [32]). ICC is a common measure of reliability, with ICCs > 0.7 indicating suitability for use within a clinical environment [33]. Additionally, relative technical error of measurement (TEM), commonly used for assessing repeatability in kinanthropometry [34], was also calculated [35]. Finally, for the acceptability data, a one sample *t*-test was used to assess significant differences from respondents’ opinions to statements and 'neither agree or disagree'.

Results

There was evidence of a significant ($p < 0.05$) fixed systematic difference between mid-trunk volumes estimated with the depth camera-based system and 3DMD, with greater volumes reported with the depth camera system (16.4 ± 2.6 vs 15.8 ± 2.5 L - Figure 3). However, there was excellent correlation between volume estimates ($r^2 = 0.997$) and little evidence of proportional bias (Least Products Regression $b = 0.96$, 95% CI 0.92-1.01). The 95% Limits of Agreement were 0.11 - 0.98 L.

**** insert figure 3 near here ****

The depth camera system was highly repeatable (Figure 4), indicated by a low typical error (mean = 0.192 L 95% CI = 0.170 - 0.219), very high ICC (>0.999) and low relative TEM (0.64 ± 0.13%).

**** insert figure 4 near here ****

Fifty-two participants (95% who completed the questionnaire) preferred to be measured using 3D surface imaging rather than the tape measure. Figure 5 highlights all responses were in a direction which indicated 3D surface imaging was acceptable. When responding to the statement ‘I was happy to be scanned' and 'I felt comfortable being scanned' participants significantly agreed ($p < 0.01$). However, participants significantly disagreed with 'The scanning procedures were distressing' ($p < 0.01$). Participants 'would feel more confident in my results if scanning was included' and agreed that 'scanning would improve the feedback about my weight status' ($p < 0.01$). Finally, participants agreed that 'regular scanning would motivate me to lose weight' and 'regular scanning should be included as part of my weight loss programme' ($p < 0.01$).

**** insert figure 5 near here ****

Discussion

The aim of this study was to investigate the feasibility of using low-cost depth camera 3D surface imaging in people with obesity. Although it was not possible to include people with obesity in the validity protocol, our results indicated good agreement between the depth camera and gold standard 3DMD systems. In the second experiment, the depth camera system demonstrated high repeatability when imaging people with obesity. Combined with the data on acceptability, the results suggest it is feasible to use depth camera based 3D surface imaging systems with people with obesity.

The depth camera system demonstrated good agreement with 3DMD. Significantly greater volumes were measured with the depth camera system but the bias was fixed rather than proportional. This is in agreement with a previous study of thigh volume [23]. Bullas et al. [23] postulated that the overestimation might stem from hardware limitations and potential calibration inaccuracies, but the reason for consistent overestimation was not clear. Nonetheless, the excellent correlation between systems (r^2 = 0.997) strongly suggests the depth camera system would show excellent agreement with the 3DMD system, following appropriate correction using a simple linear model. Similar good agreement with criterion measurements has been demonstrated for other 3D surface imaging systems, including relatively expensive systems based on depth cameras [17-18]. Our results provide further evidence that 3D surface imaging has great potential for quick and accurate body measurements in people with obesity. Moreover, the results demonstrate that valid measurements can be obtained using low cost, flexible, scalable (depth cameras can be added or removed) and reconfigurable systems comprising multiple, off-the-shelf consumer depth cameras.

The depth camera system was also highly repeatable when imaging people with obesity. The relative TEM was small (0.64 ± 0.13%), comparable to studies in which similar depth camera systems were used to measure thigh (TEM = 0.77% [23]) and mid-trunk volume (TEM = 0.88% [21]) in young, healthy participants. These results are promising as they are better than the minimum precision required by an International Society for the Advancement of Kinanthropometry practitioner (Level 1, < 2%; Level 2-4, < 1% TEM [34]). However, this interpretation is made with caution because the criteria are based on traditional anthropometrics, such as lengths and girths, and no criteria are published for volume. Regardless, the ICCs indicated the depth camera system exceeded the requirements for clinical acceptability [33].

There is a paucity of evidence on the acceptability of 3D surface imaging. Wells et al. [8] assessed the acceptability of 3D surface imaging for measurement of body shape in children but based solely on participation rates [8]. We undertook extensive searching of the peer reviewed literature to obtain a validated and reliable questionnaire that could be used in the present study. To the author's knowledge, no questionnaire exists so an in-house questionnaire was developed to explore acceptability. It is important to elucidate whether participants would benefit from being scanned as part of routine obesity monitoring and our results suggest 3D surface imaging is acceptable to people with obesity because the frequency distribution and significance for all scanning questions was positive. However, the findings may be biased since only those who volunteered completed the questionnaire, rather than all who were approached to participate. More importantly, there are many aspects which should be considered while assessing acceptance, including issues such as individual privacy perception levels, confidence with the technology used and other influences such as age and gender which were not considered and will be explored in the future. Finally, despite inviting participants to expand on their experiences and explain their Likert scale responses, there was limited engagement. Thus, there is scope to undertake a qualitative study to further understand the acceptability of the scanning system.

Experiment one sampled people without obesity. It was not practicable for participants from the obesity clinic to visit the laboratory housing the 3DMD system. Notwithstanding the difficulties in participants travelling to the laboratory, the mid-trunks of many people with obesity could not be imaged by the 3DMD system as they exceeded the maximum possible data collection volume. Importantly, though, a benefit of only imaging people with obesity with the depth camera system in the clinic was that perceptions of acceptability were not influenced by lab-based collection with the 3DMD system. Nonetheless, there was crossover in the mid-trunk volumes in the participant samples for experiments 1 and 2 – which can be observed in the mid-trunk volume data shown in figures 3 and 4. Taken together with the evidence of a lack of proportional bias, this suggests the findings from experiment 1 extend to people with obesity. A further limitation to this feasibility study is that only one of many potential anthropometric parameters was considered. However, mid-trunk volume was measured because this region is particularly difficult to model in people with obesity, owing to large variations and an asymmetric, eccentric shape. Although we suggest the findings related to mid-trunk volume are likely to extend to other regions of the body and different anthropometric parameters, more work is required to confirm this. Finally, the percentage of participants who volunteered to take part in the study was not recorded which might also reflect acceptability. However, the reasons for not participating are likely to go beyond simply acceptability due to the recruitment strategy, for instance, lack of time.

In summary, the results of this preliminary study suggest it is feasible to use cheap, readily accessible depth camera 3D surface imaging to monitor the body size and shape of people with obesity. The technique is valid and repeatable and its use is acceptable to participants. Moreover, it is possible to use a low cost 3D surface imaging system in a clinic. Multiple off-the-shelf consumer depth cameras (cost per unit ~£150) were used, which is simple, low cost, scalable and flexible. More or fewer cameras can be used and they can be reconfigured to image objects and body segments of different size and shape. Follow-up work should use 3D surface imaging to monitor the effectiveness of weight management interventions, either in a clinical or laboratory setting. Future research should also investigate the effectiveness of 3D surface imaging as a method of encouraging weight loss and adherence to weight management programmes. This research will explore the extent to which 3D surface images taken over the course of a weight management programme could aid motivation and thus weight loss.

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Figure legends

Figure 1: The 3D surface imaging system. a) the system in the lab, mounted on an aluminium frame, within the 3DMD, gold standard system. b) the system set-up in the local obesity clinic, showing the four depth cameras mounted on tripods, connected to a single, standard computer.

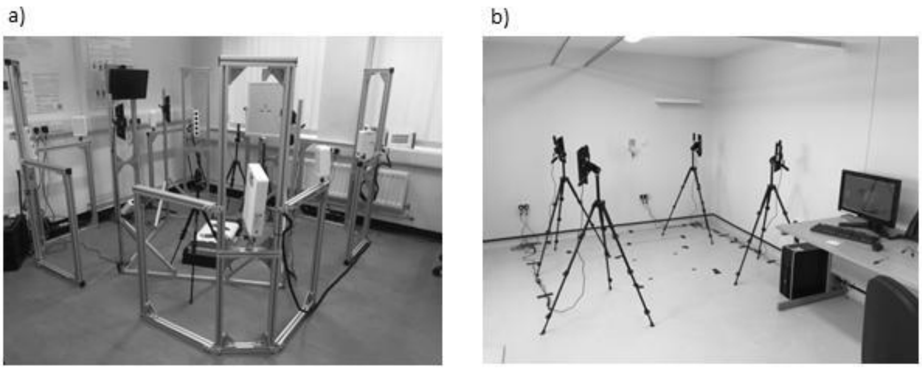

Figure 2: 3D point cloud analysis. a) An example 3D point cloud from the depth camera system, illustrating the inferior/superior segmentation planes b) Example 2D cross-section. White dots represent the raw data points. The grey line represents the cubic spline used to define the surface of the body.

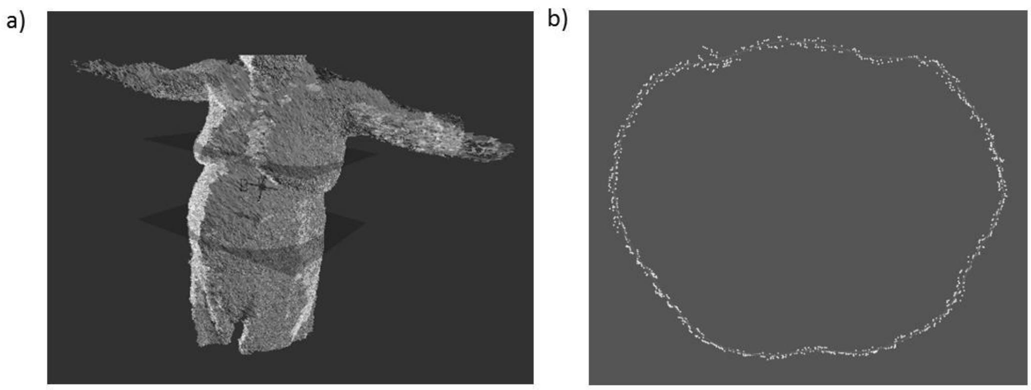

Figure 3: Agreement between depth camera and 3DMD estimates of mid-trunk volume. Dashed line: identity, solid line: least products regression line ($y = 0.96x + 0.07$).

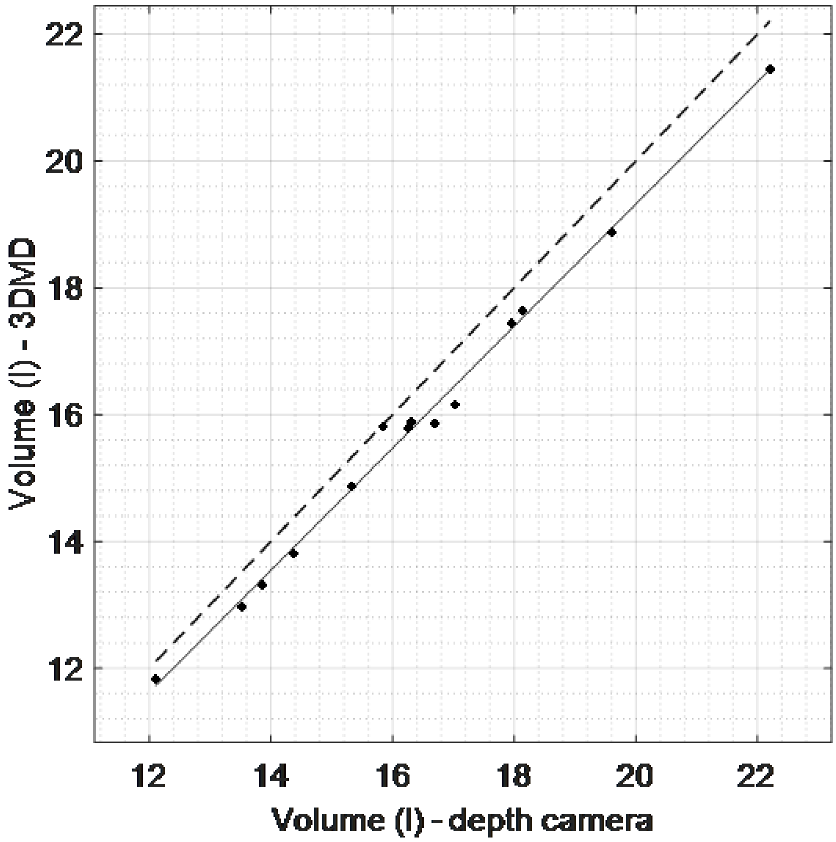

Figure 4: Mid-trunk volume for all participants across the three repeated 3D surface images black closed circles = surface image 1, black open circles = surface image 2 and grey closed circles = surface image 3.

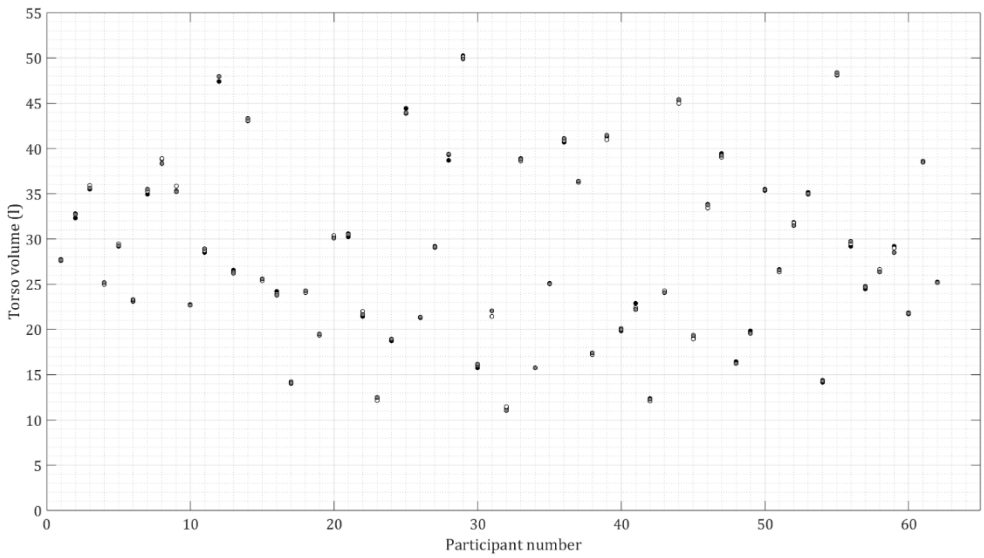

Figure 5: The acceptability of depth camera based 3D surface imaging to people with obesity