

## **Validity and repeatability of a depth camera based surface imaging system for thigh volume measurement**

BULLAS, Alice <<http://orcid.org/0000-0003-2857-4236>>, CHOPPIN, Simon <<http://orcid.org/0000-0003-2111-7710>>, HELLER, Ben <<http://orcid.org/0000-0003-0805-8170>> and WHEAT, Jonathan <<http://orcid.org/0000-0002-1107-6452>>

Available from Sheffield Hallam University Research Archive (SHURA) at:

<https://shura.shu.ac.uk/11532/>

---

This document is the Accepted Version [AM]

### **Citation:**

BULLAS, Alice, CHOPPIN, Simon, HELLER, Ben and WHEAT, Jonathan (2016). Validity and repeatability of a depth camera based surface imaging system for thigh volume measurement. *Journal of Sports Sciences*, 34 (20), 1998-2004. [Article]

---

### **Copyright and re-use policy**

See <http://shura.shu.ac.uk/information.html>

**Validity and repeatability of a depth camera based surface imaging system for thigh  
volume measurement.**

ALICE M BULLAS, SIMON CHOPPIN, BEN HELLER and JON WHEAT\*.

*Centre for Sports Engineering Research, Sheffield Hallam University, UK.*

Running Title: Validity and repeatability of thigh volume measures.

Word Count: 3738 (inc. citations, exc. references, tables, figures and captions)

**Ms. ALICE M BULLAS**

**Affiliation:** Centre for Sports Engineering Research, Sheffield Hallam University, UK.

**Telephone Number:** +44 (0)114 225 2355 **Email Address:** [a.bullas@shu.ac.uk](mailto:a.bullas@shu.ac.uk)

**Dr. SIMON CHOPPIN**

**Affiliation:** Centre for Sports Engineering Research, Sheffield Hallam University, UK.

**Telephone Number:** +44 (0)114 225 4405 **Email Address:** [s.choppin@shu.ac.uk](mailto:s.choppin@shu.ac.uk)

**Dr. BEN HELLER**

**Affiliation:** Centre for Sports Engineering Research, Sheffield Hallam University, UK.

**Telephone Number:** +44 (0)114 225 4435 **Email Address:** [b.heller@shu.ac.uk](mailto:b.heller@shu.ac.uk)

**Dr. JON WHEAT (Corresponding Author \*)**

**Affiliation:** Centre for Sports Engineering Research, Sheffield Hallam University, UK.

**Postal Address:** Centre for Sports Engineering Research, Sheffield Hallam University,  
Collegiate Hall, Collegiate, Sheffield, S10 2BP

**Telephone Number:** +44 (0)114 225 4330 **Email Address:** [j.wheat@shu.ac.uk](mailto:j.wheat@shu.ac.uk)

**Abstract**

Complex anthropometric measures, such as area and volume, can identify changes in body size and shape that are not detectable with traditional anthropometric measures of lengths, breadths, skinfolds and girths. However, taking these more complex measures with manual techniques (tape measurement and water displacement) is often unsuitable. Three dimensional (3D) surface imaging systems are quick and accurate alternatives to manual techniques but their use is restricted by cost, complexity and limited access. We have developed a novel low cost, accessible and portable 3D surface imaging system based on consumer depth cameras. The aim of this study was to determine the validity and repeatability of the system in the measurement of thigh volume. The thigh volumes of 36 participants were measured with the depth camera system and a high precision commercially available 3D surface imaging system (3dMD). The depth camera system used within this study is highly repeatable (technical error of measurement of  $< 1.0\%$  intra-calibration and  $\sim 2.0\%$  inter-calibration) but systematically overestimates ( $\sim 6\%$ ) thigh volume when compared to the 3dMD system. This suggests poor agreement yet a close relationship, which once corrected can yield a usable thigh volume measurement.

**Keywords:** Kinanthropometry, Anthropometry, Depth Camera, 3D Body Scanning, Surface Imaging.

## **Introduction**

Kinanthropometry is an academic discipline that uses anthropometric measures to determine the relationship between human structure and movement (Stewart, 2010). The description and analysis of body dimensions of sports populations is vital, not merely to monitor training, sports performance and talent identification, but to understand the evolution and development of sport (Norton & Olds, 2001). Commonly, kinanthropometric investigations have used a 'traditional' model of anthropometric analysis: the measurement of lengths, breadths, skinfolds and girths, as well as calculations based on these measures such as body mass index (BMI) and somatotype. However, more complex anthropometric measures, such as volume and surface area, can identify changes in body size and shape that might otherwise go unnoticed by the traditional model (Rønnestad, Hansen & Raastad, 2010; Schranz, Tomkinson, Olds, Petkov & Hahn, 2012). Consequently, recent literature (Schranz et al., 2012) has suggested the use of a 'new' model of anthropometric analysis within kinanthropometry studies: the measurement of traditional anthropometric measures alongside more complex anthropometric measures, such as area and volume.

The new model of anthropometric analysis can be conducted using manual techniques, such as tape measurements and water displacement, or digital techniques, such as body scanning and surface imaging. Manual tape measurement requires minimal, low-cost equipment (tape measures, callipers), is easy to perform due to standardised procedures and guidelines, is portable and, until recently, has been the only technique available to measure simple anthropometric measures. However, manual tape measurement is time consuming, requires direct physical contact and is heavily dependent upon the training and experience of the measurement personnel (Maylia, Fairclough, Nokes & Jones, 1999). Additionally, the predictive equations used to estimate complex anthropometric measures from tape

measurements are usually based on the average of a small number of samples and are highly population specific, thereby are only valid when used on the same population. Water displacement is regarded as the 'gold standard' method of volume measurement. Nonetheless it is time consuming, lacks standardised procedures and guidelines and is not suitable for individuals with wounds or skin diseases (Kaulesar Sukul, den Hoed, Johannes, van Dolder & Benda, 1993). Furthermore, water displacement is only capable of directly measuring volume, therefore also relies on predictive equations to estimate other complex anthropometric measures, such as surface area. As a result, the use of manual techniques for obtaining more complex anthropometric measures is questionable (Olds & Rogers, 2004). It has been suggested that digital techniques should be used (Olds & Rogers, 2004; Stewart, 2010).

Body scanning and surface imaging systems create 3D digital images quickly, from which many anthropometric measures can be directly extracted. In addition, these systems allow retrospective analysis of data, the opportunity for contactless measurement and the ability to produce a digital representation of body changes over time, which are all unfeasible through manual techniques (Robinette, 2013). There are many different systems available: laser, stereo-photogrammetry, stereo-radiography, millimetre wave and light based. Each system uses different methods to generate digital 3D images: the deformation of laser lines by the body, the stitching together of multiple stereo-camera images, the collation of x-ray images, the registration of the electromagnetic radiation (millimetre waves), the time-of-flight principle and the deformation of pseudo-structured light patterns (Daanen & Ter Haar, 2013). However, even though some have translated from fixed lab instruments into commercially available portable devices, these systems remain expensive, \$10,000 - \$200,000 and

subsequently are rarely used within kinanthropometry research or practice (Daanen & Ter Haar, 2013).

Depth cameras are low cost light based cameras that use the time-of-flight principle or a pseudo-structured light pattern, and computer vision techniques / algorithms to capture colour images and depth information to create digital 3D point clouds of the external geometry of the body. They are readily available within a number of consumer technologies (e.g. Microsoft Kinect) and can be used to create affordable 3D body surface imaging systems (Choppin, Probst, Goyal, Clarkson & Wheat, 2013; Clarkson, Choppin, Hart, Heller & Wheat, 2012; Clarkson, Wheat, Heller & Choppin, 2015). Several studies have investigated the use of depth camera based surface imaging systems in the measurement of anthropometric parameters, demonstrating favourable results when compared to and laser systems (Clarkson, Choppin, Hart, Heller & Wheat, 2012; Robinson & Parkinson, 2013) and favourable but overestimated results when compared to manual measures (Bullas, Choppin, Heller, Clarkson & Wheat, 2014; Clarkson et al., 2015). Consequently, a depth camera based surface imaging system appears to be the most suitable method of conducting the new model of anthropometric analysis within kinanthropometry studies.

Although a wide array of complex measures are available within the new method of anthropometric analysis, the majority of previous kinanthropometry studies have concentrated on the measurement of volume, potentially due to its importance in physical movement. For example thigh volume has been used as part of descriptive kinanthropometry of population groups (Schranz et al., 2012), and within applied analysis to investigate the effects of ageing on movement (Chen et al., 2011), exercise interventions (Messier et al., 2013) and sporting performance (Basset, Billaut & Joannis, 2014; Schranz et al., 2012). The

aim of this study was to determine the validity and reliability of a low cost depth camera based 3D surface imaging system in conducting the new model of anthropometric analyses, in particular thigh volume measurement within kinanthropometry.

## **Methods**

### *Participants*

Through convenience sampling, 36 healthy recreationally active volunteers participated in this study (Table 1). All volunteers were screened to determine their suitability for participation and required to provide written informed consent. Participants were required to be over the age of 18 years and able to stand unaided, as all measures were conducted standing. All procedures were approved by Sheffield Hallam University Research Ethics Committee.

\*\*\*\* Table 1 near here \*\*\*\*

### *Research design*

Each participant attended one 60 minute testing session. To determine the validity and repeatability of thigh volume measures obtained by the depth camera system participants had the thigh volume of both legs measured by the depth camera system and a high precision commercially available surface imaging system - 3dMD (3dMD Inc., Atlanta, GA, USA). Although the 3dMD system is not a 'gold standard' method, it is a high-precision system that is a valid and reliable tool for volume measurement (Van der Meer, Dijkstra, Visser, Vissink & Ren, 2014). Traditionally, investigations into volume would use water displacement, the 'gold standard' technique for volume measurement, despite its limitations discussed previously. However, as the aim of this study was to determine the suitability of a depth

camera system in conducting the new model of anthropometric analysis, of which volume is only one measurement, it was decided that comparison should be made against a method also capable of conducting the new model of anthropometric analysis. Thigh volume was selected due to its prevalence as a measurement within previous kinanthropometry literature (Coelho-Silva et al., 2013; Rønnestad et al., 2010;). Data were collected in 3 sets; each set consisted of 3 scans of each leg, separated by a recalibration of the depth camera system (Figure 1). Thus, a total of 9 scans, per method, per leg, were acquired for each participant.

\*\*\*\* Figure 1 near here \*\*\*\*

### *Measurement methods*

#### *3dMD system*

3dMD (3Q Technologies Inc., Atlanta, GA) is a surface imaging system consisting of 5 synchronised modular units, each containing 3 machine vision cameras, placed around a square 258 x 258 cm aluminium Bosch (Bosch Rexroth AG) strut frame (Figure 2), using a single computer (64 Bit Windows 7 Professional I7 4 Core CPU @ 3.6GHz 8GB RAM). Calibration and data collection was conducted using 3dMD acquisition software. The calibration procedure followed 3dMD guidelines using a calibration plate (Figure 3) and was conducted at the start of every testing day and then approximately every 2 hours thereafter.

\*\*\*\* Figure 2 near here \*\*\*\*

\*\*\*\* Figure 3 near here \*\*\*\*

### *Depth camera (Kinect) system*

The depth camera system was developed in-house (the Centre of Sports Engineering Research, Sheffield Hallam University, UK) and was similar to that used within previous investigations (Bullas et al., 2014; Clarkson et al., 2012). The system consisted of four depth cameras (Microsoft Kinect, Microsoft Corporation, Redmond, USA) vertically mounted 122 cm above the ground at each corner of a square aluminium Bosch strut (Bosch Rexroth AG) frame (141 x 141 cm) (Figure 2) and connected to a single computer (64 bit, i5 4-core CPU running at 3.4 GHz with 8 GB of RAM and an Nvidia Geforce GTX 650 graphics card). This layout was adopted to provide the optimum compromise between the number of depth cameras and the field of view.

KinAnthroScan - custom software created in-house using the Microsoft Kinect software development kit (Microsoft Corporation, Redmond, USA), facilitated calibration and data collection. The calibration procedure involved two stages. First, a point cloud of a calibration object (4 polystyrene spheres connected by a narrow metal pole - Figure 3) was obtained in nine positions throughout the calibration volume. The centre of each sphere was found in each camera's local coordinate system using custom-written algorithms. This resulted in 36 common points across all four cameras. The relative position and orientation of the cameras was estimated using a common rigid body transformation technique (Spoor and Veldpaus, 1980) and optimised using a RANSAC approach (Fisher & Bolles, 1981). Similar to that detailed in Clarkson et al., (2015). Second, estimates of the relative position and orientation of the cameras were further refined by imaging a more complex object (mannequin chest) and updating the calibration using an iterative closest point algorithm (Besl & McKay, 1992). Full calibration was conducted at the start of each testing day and in between each data collection set, approximately every 10 minutes. During data collection the four depth cameras collected

data sequentially, resulting in a total data collection time of approximately 900ms. This avoided interference caused by the overlapping pseudo-structured infrared light projected by multiple Kinect cameras.

### *Measurement protocol*

The thigh segment was defined using International Society for the Advancement of Kinanthropometry (ISAK) standardised anthropometric locations of the upper thigh: 1 cm distal to the gluteal fold site (Stewart, Marfell-Jones, Olds, & de Ridder, 2011, pp.85), and upper knee circumference: midpoint of the superior border of the patella (Stewart et al., 2001, pp.465). This method differs slightly from that used within biomechanical modelling or mechanical analysis, in which the thigh segment is segmented at the epicondyles of the knee and the upper aspect of the 'thigh flap' (area encompassed by the anterior superior iliac spine, hip joint or greater trochanter, and the gluteal furrow) (Wu & Cavanagh, 1995). However, definition of the thigh based upon measures similar to ISAKs standardised anthropometric locations is more popular within kinanthropometry literature (Chen et al., 2011; Coelho-E-Silva et al., 2013). These locations were manually palpated and marked directly onto the posterior and anterior aspect of the segment using crosses made with pencil (~1.5 x 1.5cm). Coloured sticky markers (~1.0 x 1.0cm) were affixed to the centre of each cross to ensure all marked points were visible in the 3D surface images. During all procedures participants were required to wear shorts. These were secured above the uppermost marker point where necessary. All marking procedures were conducted by a level one ISAK kinanthropometrist.

Participants stood on one leg during measurement, with their arms raised above their hips (Figure 2). The second leg was raised and placed on a higher platform (Figure 2) to avoid occlusion by the contralateral limb. This position was adopted on a raised platform to ensure

that participants' thighs were within the calibrated volume of both systems. Participants were asked to visually focus on small circular coloured wall-mounted markers, as focusing gaze on a stationary target during standing reduces postural sway (Thaler, Schütz, Goodale, & Gegenfurtner, 2013). The depth camera system was positioned within the 3dMD system (Figure 2) to facilitate near-concurrent data collection. It was not possible to collect entirely simultaneously as each system uses different structured light patterns. The depth camera system (~900ms data collection time) was triggered first, followed by the 3dMD system (~15ms data collection time). The systems were manually triggered, resulting in a total data collection time of approximately 2seconds.

### *Analysis*

Each scan was manually digitised; manual identification of marked landmarks in each 3D image by a single researcher within KinAnthroScan software. For the depth camera data, thigh volumes were calculated in KinAnthroScan which uses Green's equations to calculate volume using the method outlined by Crisco & McGovern (1998). Briefly, the 3D point cloud of the thigh (proximal and distal ends defined by the digitised 'upper thigh' and 'upper knee circumference' landmarks, respectively) was segmented into slices (1 mm thick) along the long axis of the segment. Each slice contained 2D coordinates of the raw points from the depth cameras. Smoothing splines - one for each contour - created collections of smoothed points. These data were then used in a discrete equation to calculate the volume of the thigh across all slices (Crisco and McGovern, 1998).

For the 3dMD data, Geomagic Studio 8 (Raindrop Geomagic, USA) was used to calculate thigh volume. Geomagic was selected as it is one of the fastest, most accurate and user-friendly commercially available software technologies (Geomagic, 2015). Within Geomagic,

following the closure of the segmentation plane, triangular meshing and the creation of a watertight mesh, volume was computed using the proprietary method.

Following the extraction of thigh volumes, a battery of agreement and repeatability tests were conducted: Mean thigh volumes, raw and absolute mean differences, technical error of measurement (TEM %) (Stewart & Sutton 2012) and statistical difference testing (t-tests) were calculated within Microsoft Excel (2010, Microsoft Corporation, USA) and SPSS software (version 21.0, IBM, USA). To explore the nature of any differences Bland-Altman and ordinary least products regression (OLP) analyses were conducted in Microsoft Excel and MATLAB (version 13.0b, Mathworks, USA), following the guidelines of Bland and Altman (1999) and Ludbrook (1997, 2010) respectively.

## **Results**

The female and male data demonstrated statistically significant differences ( $p < 0.05$ ) in both absolute size and the degree of agreement between the systems (Table 2). Consequently, the results from each sex are presented separately. Furthermore, as the left and right sides of the thigh produced similar results, the results from both sides are presented together to aid presentation and interpretation of the data.

### *Agreement*

Thigh volumes were significantly different ( $p < 0.05$ ) between the systems (Table 2).

\*\*\*\* Table 2 near here \*\*\*\*

The Bland Altman plots of thigh volume measurements demonstrated both statistically significant fixed and homoscedastic proportional bias between the two methods in both female (Correlation  $R = 0.46$ ,  $p=0.00$ . Slope = 0.05,  $p=0.00$ . Intercept = 41.56,  $p= 0.05$ ) and male participants (Correlation  $R = 0.48$ ,  $p=0.00$ . Slope = 0.06,  $p=0.00$ . Intercept = 31.97,  $p= 0.31$ ). This was reiterated by the OLP analysis that suggested the presence of a fixed and minor proportional systematic bias in both female (intercept  $a' = -40.98$ , CI -80.12 - -2.25, slope  $b' = 0.95$ , CI 0.94 - 0.96) and male participants (intercept  $a' = 30.13$ , CI -28.28 - 88.53, slope  $b' = 0.94$ , CI 0.93 - 0.965). To investigate this bias further Bland Altman ratio plots were calculated (Figure 4). This transformation identified the depth camera system to be systematically overestimating thigh volume by a mean of ~6%

\*\*\*\* Figure 4 near here \*\*\*\*

### *Repeatability*

The depth camera system demonstrated larger TEM (%) values than the 3dMD system (Table 3). No statistically significant differences were demonstrated either intra-calibration or inter-calibration sets (Table 3).

\*\*\*\* Table 3 near here \*\*\*\*

### **Discussion**

The aim of this study was to determine the validity and reliability of a low cost, depth camera based 3D surface imaging system in conducting new model of anthropometric analysis, in particular thigh volume measurement. The thigh volumes of the right and left legs of 36 participants were captured by the depth camera system and compared with measures obtained

by a high precision commercially available 3D surface imaging system (3dMD). Overall, the depth camera system demonstrated highly repeatable but systematically greater thigh volumes than the 3dMD system.

Statistically significant differences were demonstrated between the sexes in both absolute size and the degree of agreement between the two methods. It is possible this is attributable to differences in balance, absolute size, morphological characteristics, and / or surface texture (Nguyen & Shultz, 2007; Tur, 1997; Kollegger, Baumgartner, Wöber, Oder & Deecke, 1992), but future work is required to confirm this. These differences, however, are relatively consistent and do not appear to impact the interpretation of the validity and repeatability of the depth camera system.

A statistically significant systematic overestimation of thigh volume (~6%) was demonstrated by the depth camera system relative to the 3dMD system. Similar systems based on Microsoft Kinect depth cameras have been associated with similar findings related to the measurement of circumferences of solid objects (e.g. cylinders: Clarkson et al., 2015) and human body segments (Bullas et al., 2014), in addition to the volumes of mannequin (Choppin et al., 2013) and human body segments (Clarkson et al., 2012). Although it is possible to correct the fixed and proportional systematic bias using a linear model to yield a usable thigh volume measurement, the cause of the difference between the depth camera and 3dMD systems is not clear. Previous unpublished work, which analysed 3dMD data in both KinAnthroScan and Geomagic, demonstrated no statistically significant differences between the volume measures calculated. Consequently, the authors do not believe the fixed overestimation of the depth camera system to be associated with the analysis software. The authors postulate that the

fixed overestimation may stem from hardware limitations, potentially an inaccuracy within the calibration procedure. However, further work is required to confirm this.

The depth camera system demonstrated high intra-calibration repeatability (0.77% TEM). This is less repeatable than the 3dMD system (0.37% TEM) but similar to previous studies such as Clarkson et al., (2014) which reported a TEM of 0.88% in the measurement of mid-torso volume. With regards to inter-calibration repeatability the depth camera system demonstrated a TEM of 1.98%. This is greater than the inter-calibration repeatability demonstrated by the 3dMD system (0.52% TEM). Clarkson et al., (2015) demonstrated intra-calibration TEM of 0.42% and inter-calibration TEM of 1.04% when measuring a cylinder representing the upper leg. The larger TEM (%) demonstrated within this study may be attributed to a different surface texture and postural sway.

No study has investigated the natural daily variation of thigh volume or identified the minimum clinical difference important in thigh volume measurement. Furthermore, currently no international standards exist on the acceptable reliability required by measurement systems for complex anthropometric measurements, as does for traditional anthropometric measures (ISO 20685-1, International Standards Office, 2010). As a result it is difficult to determine, with confidence, if the intra and inter-calibration repeatability demonstrated is high enough to allow the measurement and detection of true change, or if this would be masked by the system's variability. In kinanthropometry, repeatability is assessed using the ISAK criteria (Stewart & Sutton, 2012). Based on these criteria the depth camera system demonstrated high intra-calibration repeatability - better than the minimum precision required at ISAK level 2 and above: TEM of less than or equal to 1%, post examination (Gore et al., 2002; Stewart & Sutton, 2012). Additionally, it demonstrated moderate inter-calibration

repeatability, equal to that of a level 1 ISAK kinanthropometrist; TEM of less than or equal to 2%, post examination (Stewart & Sutton, 2012). However, these interpretations should be judged with caution, as the criteria are based on ‘traditional’ anthropometric measures - lengths, breaths, skinfolds and girths - with no criteria published for volume.

### *Limitations*

This study has a number of limitations that require consideration. First, to reduce the risk of occlusion, physical support for participants was not provided, increasing the risk of postural sway and movement artefacts within the 3D images. This would lead to reduced validity and repeatability. Although visual inspection indicated only a minor presence of motion artefacts in a limited number of depth camera images, participant movement would have a greater influence on the depth camera system due to its longer data collection duration than the 3dMD system, ~900ms compared to 15ms respectively. Therefore, future investigations should include some form of hand support. Furthermore, this study has focused solely on thigh volume, which is only one of many anthropometric measures possible within the new model of anthropometric analysis. Thus, results of this study suggest that depth camera systems are suitably reliable and repeatable for measuring the thigh volume and only that they might be for taking other complex anthropometric measurements in kinanthropometry. However, further work is required to confirm this.

### *Application*

The use of a depth camera based surface imaging system in kinanthropometry investigations may be beneficial in a number of contexts. A recent example is Basset et al., (2014) which explored the relationship between body morphology and sporting performance in endurance cycling. A depth camera system would be an affordable, accessible and portable alternative

method to the manual methods used by Basset et al., (2014). It would eliminate population-specific predictive equations to calculate volume; often unsuitable for use on atypical population groups such as athletes. This allows for quicker data collection, thereby facilitating investigations with larger samples. Additionally in studies of children, such as Coelho-E-Silva et al., (2013) in which high cost systems may not be suitable, a depth camera system may be an affordable and portable alternative.

## **Conclusion**

This depth camera system offers multiple advantages over existing techniques: it is quick, low cost, commercially available, portable, and allows the collection of a wide-array of anthropometric measures and shape analyses. The depth camera system used within this study is highly repeatable but gives systematically greater thigh volumes than the 3dMD system. This suggests poor agreement yet a close relationship, which once corrected can yield a usable thigh volume measurement. Based upon the findings of this study and the multiple advantages over existing techniques, future kinanthropometry studies should consider the use of depth camera based surface imaging systems.

## **Disclosure statement**

The authors declare no potential conflict of interest.

## **Acknowledgements**

The authors would like to thank Terry Senior and Sean Clarkson for their assistance, and all volunteers for their participation.

## References

- Basset, F. A., Billaut, F. & Joannis, D. R. (2014). Anthropometric characteristics account for time to exhaustion in cycling. *International Journal of Sports Medicine*, 35(13), 1084-9. doi: 10.1055/s-0034-1375694.
- Besl, P. J., & McKay, N. D. (1992, April). Method for registration of 3-D shapes. In Robotics-DL tentative (pp. 586-606). International Society for Optics and Photonics.
- Bland, J. M. & Altman, D. G. (1999). Measuring agreement in method comparison studies. *Statistical Methods in Medical Research*, 8, 135-160. doi: 10.1177/096228029900800204.
- Bullas, A., Choppin, S., Heller, B., Clarkson, S. & Wheat, J. (2014, October). *Kinanthropometry applications of depth camera based three-dimensional scanning systems in cycling: repeatability and agreement with manual methods*. International Conference on 3D Body Scanning Technologies Conference, Lugano, Switzerland. doi:10.15221/14.290.
- Chen, B.B., Shih, T.T.F., Hsu, C. Y., Yu, C.W., Wei, S. Y., Chen, C. Y., Wu, C.H. & Chen, C. Y. (2011). Thigh muscle volume predicted by anthropometric measurements and correlated with physical function in the older adults. *The Journal of Nutrition, Health & Aging*, 15, 433-438. doi: 10.1007/s12603-010-0281-9.
- Choppin, S., Probst, H., Goyal, A., Clarkson, S. & Wheat, J. (2013, November). *Breast volume calculation using a low-cost scanning system*. International Conference on 3D Body Scanning Technologies, Long Beach CA, USA. doi:10.15221/13.012.
- Clarkson, S., Choppin, S., Hart, J., Heller, B. & Wheat, J. (2012, October). *Calculating body segment inertia parameters from a single rapid scan using the Microsoft Kinect*. International Conference on 3D Body Scanning Technologies Conference, Lugano, Switzerland. doi: 10.15221/12.153.
- Clarkson, S., Wheat, J., Heller, B. & Choppin, S. (2015). Assessment of a Microsoft Kinect-based 3D scanning system for taking body segment girth measurements: a comparison to ISAK and ISO standards. *Journal of Sports Sciences* . doi: 10.1080/02640414.2015.1085075
- Coelho-e-Silva, M. J., Malina, R. M., Simões, F., Valente-dos-Santos, J., Martins, R. A., Vaz Ronque, E. R., Petroski, E. L., Minderico, C., Silva, A. M., Baptista, F. & Sardinha, L. B. (2013). Determination of thigh volume in youth with anthropometry and DXA: Agreement between estimates. *European Journal of Sport Science*, 13(5), 527-533. doi: 10.1080/17461391.2013.767945.
- Crisco, J. J. & McGovern, R. D. (1998). Efficient calculation of mass moments of inertia for segmented homogenous three-dimensional objects. *Journal of Biomechanics*, 31, 97-101. doi: 10.1016/S0021-9290(97)00108-5.

Daanen, H. A. M. & Ter Haar, F. B. (2013). 3D whole body scanners revisited. *Displays*, 34, 270-274. doi:10.1016/j.displa.2013.08.011.

Fischler, M. A. & Bolles, R. C. (1981). Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. *Communications of the ACM*, 24(6), 381-395.

International Standards Office. (2010). *ISO 20685, 3-D Scanning Methodologies for Internationally Compatible Anthropometric Databases*. International Standards Office.

Kaulesar Sukul, D.M.K.S., den Hoed, P.T., Johannes, E.J., van Dolder, R. & Benda, E. (1993) "Direct and indirect methods for the quantification of leg volume: comparison between water displacement volumetry, the disk model method and the frustum sign model method, using the correlation coefficient and the limits of agreement." *Journal of Biomedical Engineering*, 15(6), pp. 477-480. doi:10.1016/0141-5425(93)90062-4.

Kollegger, H., Baumgartner, C., Wöber, C., Oder, W., & Deecke, L. (1992). Spontaneous body sway as a function of sex, age, and vision: posturographic study in 30 healthy adults. *European Neurology*, 32(5), 253-259. doi:10.1159/000116836.

Ludbrook, J. (1997). Comparing methods of measurement. *Clinical and Experimental Pharmacology and Physiology*, 24,193-203. doi: 10.1177/096228029900800204.

Ludbrook, J. (2010). Confidence in Altman–Bland plots: A critical review of the method of differences. *Clinical and Experimental Pharmacology and Physiology*, 37,143-149. doi: 10.1111/j.1440-1681.2009.05288.x.

Maylia, E., Fairclough, J.A., Nokes, L.D.M. & Jones, M.D. (1999). Can thigh girth be measured accurately? A preliminary investigation. *Journal of Sport Rehabilitation*, 8, 43–49.

Messier, S. P., Mihalko, S. L., Beavers, D. P., Nicklas, B. J., DeVita, P., Carr, J. J., Hunter, D.J., Williamson, J. D., Bennell, K. L., Guermazi, A., Lyles, M. & Loeser, R.F. (2013). Strength Training for Arthritis Trial (START): design and rationale. *BMC musculoskeletal disorders*, 14(208).doi: 10.1186/1471-2474-14-208.

Nguyen, A.D. & Shultz, S.J. (2007) Sex differences in clinical measures of lower extremity alignment. *Journal of Orthopaedic & Sports Physical Therapy*, 37, 389-398. doi:10.2519/jospt.2007.2487.

Norton, K. & Olds, T. (2001). Morphological evolution of athletes over the 20th century causes and consequences. *Sports Medicine*, 31(11), 763-783. doi: 10.2165/00007256-200131110-00001.

Olds, T. & Rogers, M. (2004). 3D anthropometry - application to health and exercise science. *Sport Health*, 22(3), 21-23. doi: 10.1016/S1440-2440(04)80126-9.

Robinette, K. M. (2013, November). *3D body scanning, past and future*. International Conference on 3D Body Scanning Technologies, Long Beach CA, USA.

Robinson, M. & Parkinson, M. B. (June, 2013). *Estimating Anthropometry with the Microsoft Kinect*. 2nd International Digital Human Modelling Symposium, Ann Arbor, Michigan, USA.

Rønnestad, B.R., Hansen, E.A. & Raastad, T. (2010). Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *European Journal of applied Physiology*, 108, 965-975. doi:10.1007/s00421-009-1307-z.

Schranz, N., Tomkinson, G., Olds T., Petkov, J. & Hahn A.G. (2012). Is three-dimensional anthropometric analysis as good as traditional anthropometric analysis in predicting junior rowing performance?. *Journal of Sports Sciences*, 30(12), 1241-1248. doi: 10.1080/02640414.2012.696204.

Spoor, C. W. & Veldpaus, F. E. (1980). Rigid body motion calculated from spatial co-ordinates of markers. *Journal of Biomechanics*, 13(4), 391-393. doi:10.1016/0021-9290(80)90020-2

Stewart, A.D. (2010). Kinanthropometry and body composition: A natural home for three-dimensional photonic scanning. *Journal of Sports Sciences*, 28(5), 455-457. doi: 10.1080/02640411003661304.

Stewart, A., Marfell-Jones, M., Olds, T. & de Ridder, H. (2011). *International Standards for Anthropometric Assessment*. International Society for the Advancement of Kinanthropometry, Lower Hutt, New Zealand.

Stewart, A. D. & Sutton, L. (2012). *Body Composition in Sport, Exercise and Health*. Routledge. Abingdon, UK.

Thaler, L., Schütz, A. C., Goodale, M. A., & Gegenfurtner, K. R. (2013). What is the best fixation target? The effect of target shape on stability of fixational eye movements. *Vision Research*, 76, 31-42.

Tur, E. (1997). Physiology of the skin—differences between women and men. *Clinics in dermatology*, 15(1), 5-16. doi:10.1016/S0738-081X(96)00105-8

Van der Meer, W. J., Dijkstra, P. U., Visser, A., Vissink, A., & Ren, Y. (2014). Reliability and validity of measurements of facial swelling with a stereophotogrammetry optical three-dimensional scanner. *British Journal of Oral and Maxillofacial Surgery*, 52(10), 922-927.

Wu, G. & Cavanagh, P. R. (1995). ISB recommendations for standardization in the reporting of kinematic data. *Journal of Biomechanics*, 28, 1257–1261. doi:10.1016/0021-9290(95)00017-C.

**Tables (with captions, on individual pages)**

Table 1: Participant descriptives.

Participant descriptives	Sex	
	Female	Male
No. of Participants	18	18
Age (years)	23 $\pm 8$	21 $\pm 4$
Stature (cm)	164.7 $\pm 5.6$	181.5 $\pm 6.5$
Mass (kg)	66.22 $\pm 20.08$	85.63 $\pm 18.88$

Table 2: The mean thigh volume  $\pm$  standard deviation (ml) for each method, and the mean difference (MD)  $\pm$  standard deviation, and statistical difference (t) and eta squared statistic between methods (\*= $p < 0.05$ ).

Set	Female					Male				
	Depth Camera	3dMD	MD ml	%	t	Depth Camera	3dMD	MD ml	%	t
1	3932.8	3703.9	228.9	6.2	23.99*	5046.8	4799.9	246.9	5.2	25.88*
	$\pm 933.9$	$\pm 876.7$	$\pm 98.4$	$\pm 2.4$	(0.89)	$\pm 871.7$	$\pm 843.0$	$\pm 87.1$	$\pm 1.9$	(0.91)
2	3933.3	3698.8	234.5	6.6	24.86*	5091.7	4807.0	284.7	5.8	26.03*
	$\pm 901.5$	$\pm 872.3$	$\pm 72.6$	$\pm 2.0$	(0.90)	$\pm 926.9$	$\pm 847.1$	$\pm 115.0$	$\pm 1.9$	(0.91)
3	3914.8	3694.9	219.9	6.1	25.29*	5077.3	4805.2	272.1	5.7	24.41*
	$\pm 926.7$	$\pm 883.0$	$\pm 109.9$	$\pm 3.0$	(0.90)	$\pm 891.0$	$\pm 843.9$	$\pm 120.4$	$\pm 2.3$	(0.90)
Mean	3927.0	3699.2	227.8	6.3	-	5072.0	4804.0	267.9	5.6	-
	$\pm 912.2$	$\pm 869.1$	$\pm 94.9$	$\pm 2.5$		$\pm 888.6$	$\pm 836.8$	$\pm 109.3$	$\pm 2.0$	

Table 3: The intra-calibration and inter-calibration TEM (%) for both scanning systems and sexes.

Method	Set	Intra-Scan calibration		Inter-Scan calibration	
		TEM (%)		TEM (%)	
		Female	Male	Female	Male
Kinect	1	$0.82 \pm 0.22$	$0.74 \pm 0.08$	-	-
	2	$0.80 \pm 0.11$	$0.78 \pm 0.09$	-	-
	3	$0.85 \pm 0.19$	$0.63 \pm 0.10$	-	-
	Mean	$0.83 \pm 0.17$	$0.72 \pm 0.11$	1.83	2.13
3dMD	1	$0.36 \pm 0.13$	$0.40 \pm 0.09$	-	-
	2	$0.36 \pm 0.12$	$0.32 \pm 0.09$	-	-
	3	$0.51 \pm 0.15$	$0.26 \pm 0.07$	-	-
	Mean	$0.41 \pm 0.14$	$0.33 \pm 0.10$	0.53	0.50

**Figure captions**

Figure 1: Flow diagram of research design.

Figure 2: Images of the equipment setup.

Figure 3: Calibration device (not to scale) for (a) the Kinect scanning system and (b) the 3dMD scanning system.

Figure 4: Bland Altman plots of the ratio of the thigh volume measurements of a) female (Correlation  $R = 0.21$ ,  $p=0.00$ . Slope =  $-0.05$ ,  $p=0.00$ . Intercept =  $1.24$ ,  $p= 0.00$ ) and b) male (Correlation  $R = 0.097$ ,  $p=0.08$ . Slope =  $0.026$ ,  $p=0.0$ ). Intercept =  $0.96$ ,  $p= 0.00$ ).