Reliability and validity of depth camera 3D scanning to determine thigh volume

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Abstract

Gross thigh volume is a key anthropometric variable to predict sport performance and health. Currently, it is either estimated by using the frustum method, which is prone to high inter- and intra-observer error, or using medical imaging, which is expensive and time consuming. Depth camera 3D-imaging systems offer a cheap alternative to measure thigh volume but no between-session reliability or comparison to medical imaging has been made. This experiment established between-session reliability and examined agreement with magnetic resonance imaging (MRI). Forty-eight male cyclists had their thigh volume measured by the depth camera system on two occasions to establish between-session reliability. A subset of 32 participants also had lower body MRIs, through which agreement between the depth camera system and MRI was established. The results showed low between-session variability (CV = 1.7%; Absolute Typical Error = 112 cm^3) when measuring thigh volume using the depth camera system. The depth camera systematically measured gross thigh volume 32.6cm^3 lower than MRI. These results suggest that depth camera 3D-imaging systems are reliable tools for measuring thigh volume and show good agreement with MRI scanners, providing a cheap and time-saving alternative to medical imaging analysis.

Introduction

Thigh volume is an important anthropometric characteristic in sport and exercise science (McCartney, Heigenhauser, & Jones, 1983; Schranz, Tomkinson, Olds, Petkov, & Hahn, 2012). It is an anthropometric marker of strength and maximal intensity exercise (Chelly, Hermassi, Aouadi, & Shephard, 2014; Chelly, Hermassi, & Shephard, 2015) and maximal-intensity exercise and health across a range of age groups (Makrides, Heigenhauser, McCartney, & Jones, 1985), genders and sub-populations (Lindemann et al., 2016). It also can be used to ascertain lean thigh volume (i.e. gross volume minus fat), which acts as a determinant of sporting performance (Dorel et al., 2005; Hopker, Coleman, Passfield, & Wiles, 2010).

Accurate and reliable measurement of thigh volume therefore is highly desirable for the routine assessment of athletes and patients. X-ray and water displacement methods are thought to be gold standard measures of limb volume, but the high radiation exposure in X-rays make it unethical and potentially dangerous to measure volume longitudinally. Additionally, water displacement is highly impractical and difficult to make precise volume measurements in short periods of time.

Medical imaging technologies (e.g. magnetic resonance imaging [MRI]) have been used to assess thigh volume (Winsley, Armstrong, & Welsman, 2003) and lean thigh volume (Eston, Rowlands, Charlesworth, Davies, & Hoppitt, 2005). Despite their ability to quantify muscle volume/mass and fat mass, they typically are unavailable for regular use in most applied settings because of expense, laborious data capture and analysis procedures, and in some cases exposure to radiation.

As such, gross thigh volume is commonly acquired by measuring a series of girth measurements around the thigh (typically near the gluteal fold, mid-thigh and patella) using a

tape measure, and then calculating the segment volume by modelling it as a frustum (or a series of frusta) (Kaulesar Sukul, den Hoed, Johannes, van Dolder, & Benda, 1993; Stranden, 1981; Winter, Brookes, & Hamley, 1991). The frustum method provides a cheap and practical method to predict bone and muscle volume of the thigh (and whole leg). The first stage of the frustum method estimates gross thigh volume by performing (typically three) requisite linear extrapolation of thigh circumference measures, however, is not representative of a complex thigh structure, where muscle hypertrophy can be local. Therefore, using the initial part of the frustum method to measure total thigh volume can mask local hypertrophy, which reduces sensitivity (Mendiguchia et al., 2013). As such, the gross thigh volume which is used as part of the frustum method should be considered an emblematic measure rather than a valid representation of thigh volume.

Three-dimensional (3D)-surface imaging systems – also known as 3D-scanning systems – offer an alternative method for obtaining measurements of thigh volume. These systems offer several benefits. They capture the complete external geometry of the thigh, data collection and analysis are fast and non-invasive, and they allow digital representations of the thigh to be stored, facilitating retrospective analysis of data. Although 3D-surface imaging systems have been used to take measurements of the human body (Hsu, Shih, & Liao, 2013), their use has been limited due to cost (ranging from £10,000 to £150,000) (Daanen & Ter Haar, 2013).Consumer depth cameras – also known as RGB-D cameras (cost about £150) – offer an alternative for inexpensive and quick measurement of 3D morphology of the human body (Bullas, Choppin, Heller, & Wheat, 2016; Clarkson, Wheat, Heller, & Choppin, 2016; Ng, Hinton, Fan, Kanaya, & Shepherd, 2016; Soileau et al., 2016; Tong, Zhou, Liu, Pan, & Yan, 2012; Wheat, Choppin, & Goyal, 2014). Several approaches have been used to obtain complete geometries of body segments from depth cameras, including moving the camera relative to a still participant or moving the participant relative to a fixed single camera (Ng et

al., 2016). An alternative that presents an important benefit of fast data collection times (which is more convenient for the participant and reduces movement artefacts) is to extrinsically calibrate several depth cameras relative to each other and perform near concurrent data capture. Bullas et al. (2016) used four extrinsically calibrated depth cameras to measure thigh volume and reported good intra-session reliability (relative technical error of measurement = 2.0%) but systemically overestimated thigh volume (6%) when compared to a gold standard 3D-surface imaging system (3dMD Ltd., 2008).

Despite these promising initial findings related to the measurement of thigh volume using inexpensive, readily accessible, depth cameras, agreement with gold standard medical imaging techniques (such as MRI) is yet to be established, and no inter-session variability has been reported. Inter-session variability is important for longitudinal assessment (McGuigan, 2017), particularly for elite athletes, where it is necessary to differentiate meaningful changes in volumes and potentially fat and fat-free volumes/mass of total thigh volume (Wroblewski, Amati, Smiley, Goodpaster, & Wright, 2011). Therefore, the aims of this study were twofold: to establish inter-session reliability of thigh volume measured using a depth camera 3D-imaging system similar to that used by Bullas et al. (2016) and to assess the agreement between measurements of thigh volume taken using MRI and the depth camera system.

Methods

Participants

Forty-eight male cyclists (*M* ± *SD*; age, 22.0 ± 4 years; stature, 1.79 ± 0.06 m; body mass, 77.8 ± 11.3 kg) were recruited for the study, all of whom participated in experiment 1. Thirty-six of those participants (*M* ±*SD*; age, 22.2 ± 5 years; stature, 1.79 ± 0.07 m; mass, 75.2 ± 10.8 kg) volunteered to participate in experiment 2. Experience varied from recreational cyclists to elite cyclists who have competed internationally in the following

disciplines: BMX, track sprint, track endurance, mountain bike and road. Before their involvement, participants were informed of the purpose and potential risks of the study and provided written informed consent. The study was approved by the institutional Research Ethics and Governance Committee.

Study Design

The study was split into two experiments to assess the reliability and validity of the depth camera system. In experiment 1, between-session reliability of the depth camera system was assessed by comparing mean thigh segment volume of the participants measured on two occasions. In experiment 2, validity of the depth camera system was assessed by comparing the thigh segment volume with that measured using a 1.5 T Signa HDxt portable MRI system.

The depth camera system used in both experiments was similar to that used by Bullas et al. (2016). It comprised four off-the-shelf, consumer depth cameras (Microsoft Kinect version 1, Microsoft Corporation, Redmond, USA) mounted vertically at each corner of a 1.41 m by 1.41 m aluminium frame (Bosch, Rexworth, AG). Each camera was connected to a single computer (Dell Vostro 470, Intel Core™ i7, 8.0 GB RAM Dell Inc., Texas, USA), running KinanthroScan software (KinanthroScan v1.0, Centre for Sports Engineering and Research, Sheffield Hallam University), which was used to extrinsically calibrate, communicate with, and obtain data from, each depth camera during 3D scan capture.

Calibration of the depth camera system followed the process described by Clarkson et al. (2016) in which 3D images of a calibration object (four polystyrene spheres mounted on a metal pole and baseplate) were obtained at nine positions in the calibration volume. The centres of the spheres were identified using a combination of image processing on the depth maps (an image containing information about the distances of objects in the scene from the

camera) and spatial optimisation within the 3D point clouds (collections of 3D points). Estimates of the sphere centre locations in each camera's local coordinate system then were used to determine the relative position and orientation of the cameras using a common rigid body transformation technique (Spoor & Veldpaus, 1980) and optimised using a RANSAC approach (Fischer & Bolles, 1981). The system was calibrated on each testing day, taking approximately 9 min to complete.

During 3D scan capture, data were collected sequentially from each depth camera, eliminating interference between the devices. This resulted in a total capture time of approximately 900 ms. For more details of the depth camera system, see Bullas et al. (2016).

Experiment 1: Inter-session Reliability

Depth Camera-Based 3D Scan Capture

To assess the test-retest reliability of the depth camera system, participants reported to the laboratory twice, separated by a minimum of 24 hours and maximum of 7 days. Participants were instructed to avoid strenuous exercise 24 hours before data collection to avoid exercise-induced swelling and therefore changes in thigh segment volume. The 3D scans were captured for the left and right thigh segment at each visit. Upon arrival at the laboratory, participants removed extraneous lower body clothing and rolled up underwear if necessary to expose the relevant thigh segment.

The inferior and superior boundaries of the thigh segment of each leg were identified by a circular marker, 1 cm in diameter, made in marker pen by the researcher to ensure the boundaries were visible on the scan image and to aid digitisation during post-scan analysis. The inferior boundary was defined as the most superior margin of the anterior patella and the superior boundary of the thigh segment was defined at a point 1 cm below the gluteal fold,

both in accordance with the standards of the International Society for Advanced Kinanthropometry (Stewart & Sutton, 2012). For consistency, the same researcher performed the anatomical marking throughout the data collection. 3D scans were captured while participants stood on an X that marked the centre of the scanner area. The limb not currently being scanned was positioned upon a nearby table, 1 m in height (straight-legged with relaxed calf muscle in contact with the table surface), to provide participants with stability and to keep the limb above the cameras' vertical field of view. The scan was then captured with this process being repeated for the contralateral limb. Before leaving, the 3D images were examined briefly to ensure that the quality was at the desired standard. If they were not, the process was repeated until the investigator was satisfied with the image quality. This process took a maximum of 10 minutes.

Post-Processing

After the capture of the 3D scans, preliminary analysis was conducted in KinanthroScan (KinanthroScan v1.0, Centre for Sports Engineering and Research, Sheffield Hallam University). This required the digitisation of two anatomical landmarks, the superior and inferior boundaries of the thigh segment region of interest. For consistency of landmark digitisation in pre-post scans, a custom programme was used to automatically place the superior landmark equidistant from the inferior (which was placed by the researcher) to replicate thigh segment length from the initial test in the second experimental session. As such, the length of the thigh segment was kept consistent and allowed for direct comparison of volumes given by the scan analysis.

This process created point clouds representing the thigh segment. We used an implementation of discrete Green's equations as reported by Crisco & McGovern (1998) to calculate thigh volume. Each thigh point cloud was segmented into multiple contours (1 mm

thickness) along the long axis of the segment. The coordinates of each point on the contour in the long axis direction (*z*) were discarded, creating a plane of 2D points for each contour. Smoothing splines were fitted to the raw 2D points, resulting in a smooth collection of points defining the surface of the thigh in each contour. Thus, the thigh was represented as an object that can be described by multiple contours (*s* where *s = 1* to *sn*, and *sn* is the total number of contours). Each contour lies on an *xy* plane and contains multiple 2D points (*p*, where *p = 1* to *pn*, and *pn* is the total number of point on a contour). The contours have *z* coordinates within the segment (mid-point of the contour along the long axis of the segment) and have consistent thickness (*dz*: 1 mm). Therefore, the coordinates of any point on the surface of the trunk are defined by *x(s,p)*, *y(s,p)* and *z(s)* and:

$$dx(s,p) = x(s,p+1) - x(s,p)$$

$$dy(s,p) = y(s,p+1) - y(s,p)$$

$$u(s,p) = \frac{x(s,p+1) + x(s,p)}{2}$$

$$v(s,p) = \frac{y(s,p+1) + y(s,p)}{2}$$

Volume can then be calculated as:

$$V = \sum_{s=1}^{sn} \left(dz \times \sum_{p=1}^{pn(s)-1} \left(-\frac{v(s,p)}{2} dx(s,p) + \frac{u(s,p)}{2} dy(s,p) \right) \right)$$

Statistical Analyses

We measured absolute reliability using absolute standard error and calculated relative reliability using coefficient of variation (CV), standardised typical error and intraclass correlation coefficient (ICC). Thresholds for CV were defined in line with previous reliability studies that have used a CV of < 5% to infer acceptable reliability (Buchheit, Spencer, &

Ahmaidi, 2010). For standardised typical error, the results were doubled prior to interpretation using modified effect size thresholds (trivial, ≤ 0.2; small, > 0.2–0.6; moderate, > 0.6–1.2; large, > 1.2) as advocated by (Smith & Hopkins, 2011). ICC was interpreted according to the following thresholds: high , > 0.90; moderate, 0.80–0.90; low, < 0.80 (Vincent, 2012). We calculated raw and relative typical error, as well as ICC, using the MS Excel Reliability spreadsheet developed by Hopkins (2015).

Experiment 2: Agreement of the Depth Camera System with MRI

Magnetic Resonance Imaging

The second part of this study assessed agreement (concurrent validity) between the depth camera system and MRI. T1-weighted MR images of both limbs of the lower body were obtained originating at the anterior-superior iliac spine and finishing at the lateral malleolus of the fibula (scan parameters: time of repetition = 600 ms; time to echo = 14 ms; image matrix 512 pixels x 512 pixels; field of view 260 mm x 260 mm; slice thickness = 5 mm; and interslice gap = 50 mm), using a mobile MR scanner at Christie Hospital, Manchester, UK (1.5 T Signa HDxt; Alliance Medical Limited, Warwick, UK). The MR scanner was operated by trained radiographers.

Participants were asked to refrain from intensive exercise in the 24 hours before the scan. Before the MRI scan, each participant had multiple capsules containing fish oil attached to each leg to mark the specific landmarks. Fish oil capsules are an effective, low-cost MRI compatible skin marker (Gilbert et al., 2011). Accordingly, the inferior land mark had fish oil capsules placed at the superior margin of the anterior patella, and the superior land mark had fish oil capsules placed on the lateral part of the thigh 1 cm below the gluteal fold. Participants lay supine with legs fully extended and strapped in position to discourage any movement that could cause image distortion.

MRI Processing

MR images were copied to open source DICOM image processing software OsiriX (OsiriX Lite 7.5.1, Pixmeo, Geneva, Switzerland), and an initial check for image quality was conducted. At this point, four participants were removed from the study due to either poor image quality or difficulty determining the inferior and superior boundaries of the thigh segment. For the remaining participants, the anatomical cross-sectional area of each thigh image was determined, in the axial plane, by manually outlining each individual image using the "closed polygon" tool. As this study was assessing whole-thigh segment volume, as opposed to that of constituent muscles, external visceral fat and connective tissue was not excluded.

Manual outlining started with the most distal slice above the knee at which the anterior superior margin of the patella was not visible and ended with the most proximal slice for which the thigh was clearly distinguishable from the gluteal muscles. The total number of slices was noted and used to determine the length of the segment (length = n x 0.5 cm; where n = number of slices, given that MR image slices were 5 mm in thickness), and so the thigh segment volume could be calculated using the volume equation: volume = cross-sectional area x height. To ensure consistency in the assessment of concurrent validity between MRI and the depth camera system, the length given by MRI analysis was mirrored when calculating thigh segment volume from the raw circumference data obtained from the scan analysis.

Statistical Analyses

We initially assessed concurrent agreement by comparing thigh segment volume as determined by the MRI technique with the mean volume of participants for which pre-post depth camera system scans were available. Of these, two were removed due to poor MRI clarity leading to a total of 32 observations. We used ordinary least square regression to determine the strength of the relationship between the criterion (MRI) and practical method (3D capture scan). We calculated overall bias, standardised and standardised error of estimate (SEE) with 95% confidence expressed absolutely as well as CV about regression in accordance with Hopkins' (2015) guidelines. Both standardised mean bias and SEE used different modified Cohen scales. Hopkins' modified Cohen scale was used to establish effect size thresholds for standardised overall bias; half thresholds of the scale were used (trivial, ≤ 0.2; small, > 0.2–0.6; moderate, > 0.6–1.2; large, > 1.2). For SEE, Hopkins' Cohen scale thresholds (trivial, < 0.1; small, ≥ 0.1–0.3; moderate, > 0.3–0.6; large, > 0.6) were used (Hopkins, 2015).

Results

Experiment 1

Thigh volume measures of both lab visits are shown in Table 1. Absolute typical error of 112 cm^3 was measured. For relative reliability, CV was 1.7%, and standardised typical error was calculated to be 0.09, which is classified as trivial effect size. ICC was 0.99 (0.99–1.0), which showed high repeatability.

Experiment 2

There was good agreement between the depth camera and MRI estimates of thigh volume (Figure 1) with the depth camera systematically measuring volume lower than the MRI by 32.6cm^3. Raw and standardised SEE were 187 (149–249) cm^3 and 0.20 (0.16–0.27),

small overall bias. SEE expressed as a CV about the regression was 3.8% (3.0–5.1%). Raw and standardised overall bias were 31 (-35–97) cm^3 and 0.03 (-0.04–0.10), respectively, which is classified as trivial. This is summarised in Table 2.

Discussion

The aims of this investigation were to establish between-session reliability of thigh volume using the depth camera system and to compare the agreement of thigh volume obtained using the depth camera system with MRI measurement.

For our first aim, results suggest that the depth camera system has high inter-session reliability when measuring thigh volume. For our second aim, there was a good agreement between thigh volume measures of the depth camera system and MRI with only a small, systematic underestimation. Taken together, our findings give researchers and practitioners confidence that depth camera 3D-imaging systems offer an inexpensive, time-saving and practical method to accurately and reliably measure gross thigh volume, making them suitable to monitor longitudinal changes.

Traditionally, gross thigh volume is more commonly estimated by applying a formula that uses three circumference measures (distal, middle, and proximal) to create frusta (Jones & Pearson, 1969; Kaulesar Sukul et al., 1993; Stranden, 1981; Winter et al., 1991). This method that predicts gross thigh volume was introduced almost half a century ago, at the time where MRI and other high-fidelity systems were unavailable or, in the case of roentgenograms, were restricted to two-dimensional images and, importantly, were hazardous. The depth camera system provides a higher resolution (i.e. more girth measuring points) which improves the measure of gross thigh volume by reducing the two major sources of error. First, it minimises inter- and intra-practitioner error as it only requires a practitioner to mark one point subsequent to the first measure of a participant rather than having to make

three separate circumference measures. Second, the higher resolution from the depth camera system gives a better representation of gross thigh morphology, capturing the non-homogenous structure and growth of the thigh, which can be lost with the frustum method (Mendiguchia et al., 2013; Wells et al., 2014).

Depth camera systems are applicable for monitoring thigh volume changes in response to training and prediction of sporting performance. They also are useful as an affordable and quick method to diagnose differences or changes in thigh volume in the clinical setting, such as trying to measure the difference between thigh volume of an individual who has suffered severe or chronic injuries in which limbs are injured or immobilized for long periods (e.g. after severe bone fractures or cruciate knee ligament tears). This also would make it applicable for practitioners, clinicians, strength and conditioning coaches, and physiotherapists to use as part of a monitoring or rehabilitation assessment battery.

Our data collection showed the depth camera system to have a good between-session variation (CV = 1.7%). This repeatability is similar to that presented by Bullas et al. (2016) who investigated the intra-session variation of a similar depth camera system reporting a CV of 2.0%. The between-session variation for the 3D scanning system is similar when measuring volume using MRI and computed tomography (CT) where typical between-session measures are about 2% when using human participants rather than cadavers (which report a < 1% repeatability). However, both Bullas et al. (2016) and Clarkson et al. (2016) reported a systematic overestimation of about 6% when comparing to volumes obtained using a gold standard 3dMD-surface imaging system and machined cylinders of known volume, respectively. The current study showed only a small, consistent and systematic overestimation of about 0.2% when compared to MRI, which suggests that both the depth camera system and MRI might systematically overestimate gross thigh volume.

There are limitations of this study that should be acknowledged. First, we assessed only one configuration of a consumer depth camera 3D-imaging system. Systems based on extrinsically calibrated consumer depth cameras can vary by the make and model, number, and positioning of the cameras. This is analogous to 3D stereo-photogrammetry systems – used for tracking movement of the body or equipment – which vary based on these factors. As with 3D stereo-photogrammetry systems, changes in the configuration of a depth camera 3D-imaging system likely would affect validity and repeatability. The results presented here, however, provide a useful, general, indication of the validity and repeatability of depth camera systems in measuring thigh volume. Nonetheless, future studies using depth camera systems should report summary information for the repeatability of the specific setup used – which is, again, analogous to good practice with stereophotogrammetry systems.

Second, like all 3D surface imaging systems – as well as other techniques such as water displacement and the frustum method – depth camera systems measure only gross thigh volume. Unlike medical imaging technologies, the composition of the thigh is unknown and, therefore, depth camera systems cannot be used to measure proportions fat and fat-free tissue directly. 3D surface scanning, however, has been used recently to estimate proportions of abdominal subcutaneous and visceral fat, by extracting from the 3D scans information about the shape as well as size of the abdominal region (Lee, Freeland-Graves, Pepper, Yao, & Xu, 2014). Future research should explore the use of similar approaches to estimate proportions of fat and fat-free tissue in the thigh from 3D scans obtained with depth camera systems.

Conclusion

Three-dimensional surface imaging systems based on consumer depth cameras offer a solution to reliably measure thigh volume longitudinally with trivial-to-small differences

from MRI measures. Furthermore, they are low cost and readily accessible, offering the potential to impact on analysis of body morphology in clinical, health and sports domains.

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No potential conflict of interest was reported by the authors

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Figure 1: Relationship between thigh segment volume as measured by the depth camera-based 3D scanning system and MR Imaging technique (R^2 = 0.96); y = -32.6 + x.

Table 1: Mean (± *SD*) thigh volume of both lab visits with coefficient of variation (CV%), absolute and standardised (stand) typical error and intraclass correlation coefficient (ICC).

Table 2: Raw and standardised overall bias and standard error of estimate