Assessment of a Microsoft Kinect-based 3D scanning system for taking body segment girth measurements : a comparison to ISAK and ISO standards

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Assessment of a Microsoft Kinect-based 3D scanning system for taking body segment girth measurements: a comparison to ISAK and ISO standards

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Abstract

Use of anthropometric data to infer sporting performance is increasing in popularity, particularly within elite sport programmes. Measurement typically follows standards by the International Society for the Advancement of Kinanthropometry (ISAK). However, such techniques are time consuming, reducing their practicality. Schranz et al. recently suggested 3D body scanners could replace current measurement techniques, however current systems are costly. Recent interest in natural user interaction has led to a range of low cost depth cameras capable of producing 3D body scans, from which anthropometrics can be calculated. A scanning system comprising four depth cameras was used to scan four cylinders, representative of the bodies segments. Girth measurements were calculated from the 3D scans and compared to gold standard measurements. Requirements of a level 1 ISAK practitioner were met in all four cylinders, and ISO standards for scan derived girth measurements met in the two larger cylinders only. A fixed measurement bias was identified, which could be corrected with a simple offset factor. Further work is required to determine comparable performance across a wider range of measurements performed upon living participants. Nevertheless, findings of the study suggest such a system offers many advantages over current techniques, having a range of potential applications.

Keywords: 3D Body scanning, Anthropometrics, ISAK, ISO, Kinanthropometry

Introduction

Measurement and characterisation of the human body within the fields of sport and physical activity has been practiced for several decades (De Nayer, 1956; Ledent and Wellens, 1922; Vandervael, 1943). Early studies typically obtained simple anthropometric measurements using tape measures and callipers, enabling the study of body shape with the use of statistical analysis and modelling (Boyd, 1980; Tanner, 1981; Weiner and Lourie, 1969).

The same measurement techniques are used today (Stewart, Marfell-Jones, Olds, and de Ridder, 2011), and the term 'kinanthropometry' has gradually been adopted (Beunen and Borms, 1990; Parlebas, 1981; W. Ross, Hebbelinck, Van Gheluwe, and Lemmens, 1972; W. Ross and Wilson, 1974) to describe the discipline, recognising the role of anthropometric assessment and statistical analysis in predicting characteristics of human movement (Beunen and Borms, 1990; Malina, 1984; W. D. Ross and Borms, 1980). Numerous recent studies relate to kinanthropometry, often investigating specific groups of athletes (Barlow, Findlay, Gresty, and Cooke, 2014; Hencken and White, 2006), or comparing anthropometric profiles of athletes to the general population (Aitken and Jenkins, 1998; Pienaar, Spamer, and Steyn, 1998; Reilly, Bangsbo, and Franks, 2000; Schranz, Tomkinson, Olds, and Daniell, 2010) to determine morphological characteristics likely to result in sporting success.

Interest in kinanthropometry is increasing, largely attributable to its applications within elite sport. For example, kinanthropometric assessment can be used within training environments to track the change in an athlete's physique over time, and in response to specific training interventions (Kerr, Ackland, and Schreiner, 1995). Other applications include elite sport talent detection and identification (Bullock et al., 2009; Mohamed et al., 2009; Pienaar et al., 1998; Williams and Reilly, 2000), talent development, and talent transfer programs (Hoare and Warr, 2000).

In response to widespread interest in kinanthropometric assessment and the need for standardisation, the International Society for the Advancement of Kinanthropometry (ISAK) was formed. ISAK defined a unified measurement protocol, reliability standards, and a series of accreditation and training courses (Stewart et al., 2011; Stewart and Sutton, 2012). Adherence to a single standard ensures that measurements are taken in the same way, enabling direct comparison of measurements (Stewart, 2007) or development of anthropometric databases to produce talent identification criteria. However, the assessment process can be lengthy – taking up to an hour per person - owing to the number of measurements required and the need to take multiple measurements at each site. Within dedicated talent identification sessions this is unlikely a problem, however, such time demands within

training or competition environments are likely prohibitive to normal activities (Schranz et al., 2010), and hence largely infeasible.

Schranz et al (2010) outline the potential for 3D scanners within competition environments, citing their significant advantages over conventional techniques. Firstly, they provide anthropometric data in a quicker and less invasive manner, making their use more feasible than current techniques (Schranz et al., 2010). Secondly, they offer the potential for greater complexity of measurement (such as segment mass and volume) which are not directly possibly with manual measurement techniques. Thirdly, they provide the ability to store an archive of 3D scans relating to a particular athlete, allowing assessment of historical trends, reassessment of measurements, or additional measurements to be taken whenever needed. However, current 3D scanners appear prohibitively expensive (Schranz et al., 2010) and typically require specialist training.

The recent interest in natural user interaction has led to the development of low cost (in the region of £200 (Amazon, 2012)) depth cameras such as the Microsoft Kinect® (Microsoft Corporation, Redmond, USA) and Asus Xtion Pro (ASUSTeK, Taipei, Taiwan), able to capture human motion in 3D (Boehm, 2012). Commonly using a combination of structured light (Shpunt and Zalevsky, 2009) and computer vision techniques (Shotton et al., 2011), they are also capable of capturing 3D scan data at a rate of 30Hz (K Khoshelham, 2010). Their launch has led to significant interest in a range of communities including: robotics (Henry, Krainin, Herbst, Ren, and Fox, 2012), body scanning (Boehm, 2012), healthcare (Labelle, 2011), and apparel (Stampfli, Rissiek, Trieb, and Seidi, 2012).

Despite this, there have been few studies investigating the validity of raw measurement data provided by such devices. Recent studies typically focus on simple measurements (such as Euclidian distances and plane fitting residuals) from single devices (Boehm, 2012; Khoshelham and Elberink, 2012), whereas a scanning system for anthropometric assessment would typically comprise multiple devices (Boehm, 2012; Clarkson, Choppin, Hart, Heller, and Wheat, 2012; Clarkson, Wheat, Heller, Webster, and Choppin, 2013; Wheat, Choppin, and Goyal, 2014), and involve more complex measurements (such as girths and surface distances), possibly leading to a compounding of error. Robinson et al (2012) stated that assessment of application specific suitability should be as close to reality as practically possible, and not rely on simple geometric tests such as those identified above. Aligned with this sentiment, the National Physical Laboratory (Teddington, Middlesex, UK) have developed the 'Phantom Man' – an object with which to assess the accuracy of commercial, full body scanners (Robinson et al., 2012). The Phantom Man is an anthropomorphic collection of rigid, metal, prismatic shapes 1.8 metres tall. Because each body segment is a simple, geometric shape it can be manufactured (and measured) very accurately. Its representative size means that scanners tested with the standard are assessed at an appropriate scale. The ISO 20685-1 standard (International Standards Office, 2010) aids such assessment, defining defines data collection protocols and acceptable reliability standards for measurements from 3D body scanners. However, there are few commercial 3D body scanners which claim adherence to the standard.

A recent study by Clarkson et al (2013) provides the most applicable assessment, using a scanning system comprising four Microsoft Kinect® depth cameras to take scans of a machined aluminium cylinder, representative of a large body segment. Circumference measurements from the system were compared to gold standard measurements (± 0.01 mm) manually taken with callipers. The results showed good reliability (± 3.5 mm), and the presence of a systematic measurement overestimation (9.5 mm). Nevertheless, the study suggested scanning systems comprising depth cameras can be used to scan and measure the human body for kinanthropometric assessment.

Ostensibly, for a 3D body scanning system to be accepted within the Kinanthropometry community it should adhere to the widely accepted ISAK standards. Similarly, a system should also meet requirements of the ISO standards.

The aim of this study was to determine whether a 3D body scanning system based upon four depth cameras was capable of meeting ISAK and ISO standards when taking girth measurements of typical

body segments. Accuracy and reliability of the scanning system was assessed, determining the system's validity and adherence to ISAK and ISO standards. If the results of this study show the scanning system to adhere to ISAK and ISO standards, then subject to comparable results from further studies it could be used to replace current techniques, offering many advantages, and opening up numerous possibilities for kinanthropometric assessment within training and competition environments.

Methods

Prior to commencing the study, ethical approval was gained from the faculty research ethics committee.

Scanning System

The Microsoft Kinect® depth camera was chosen for this study, owing to its low cost (~£200), support of a full software development kit, and the favourable results presented in previous studies (Boehm, 2011; Clarkson et al., 2013; Menna, Remondino, Battisti, and Nocerino, 2011).

The scanning system comprised four Microsoft Kinect® sensors mounted in a vertical orientation. The vertical orientation increased the vertical field of view, and allowed the Kinects® to be positioned closer to the objects being scanned, maximising the point cloud resolution (Khoshelham and Elberink, 2012). Each Kinect® was affixed to a tripod (figure 2), located 0.8 m from the centre of a 0.3 m x 0.3 m x 1.2 m calibrated area. Accuracy in positioning the Kinects® was not imperative in this setup process, as the later calibration process is not susceptible to out of square errors or rotation of the Kinects®. The size of the capture volume was determined from previous investigations and known to be sufficient to contain typical body segments, whilst ensuring they remain far enough from the Kinects® to permit reliable measurement of depth.

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) running custom software (created using the Microsoft Kinect® software development kit- Microsoft Corporation, Redmond, USA) was used to control the Kinects®, perform calibration, and capture scans. -The software was used to switch the Kinect's® infra-red (IR) projectors on and off during scanning to prevent interference between neighbouring sensors (Clarkson et al., 2012), resulting in a scan time of ~1 second.

Previous research has shown the Kinect's® raw depth data to exhibit significant distortion (Clarkson et al., 2013). Therefore a device specific calibration procedure (Clarkson et al., 2013) was followed prior to first use of each device, with the resulting calibration parameters used to correct the data from each device.

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

The local coordinate system of each Kinect® was aligned to a global frame. A calibration object comprising four 120 mm diameter spheres mounted on a vertical rod, figure 1a, was placed in nine different positions within the capture volume, defined such that the entire capture volume is filled with calibration points. Point cloud scans and corresponding depth images were captured by each Kinect® in each position. Sphere centres were first identified in the 2D depth images using a combination of Prewitt edge detection (sensitivity of 0.4), figure 1c, and Hough transforms (Ballard, 1981), initialised with the number of pixels a sphere is expected to occupy in the image, figure 1d. The identified 2D points were then converted to 3D using the Kinect's® integral coordinate mapping function, approximating the centre of the sphere on its front face. A Euclidian point to point minimisation technique was then used to identify the actual 3D sphere centre (Clarkson et al., 2012), figure 1e. A rigid body transformation algorithm (Challis, 1995), combined with a RANSAC point discrimination algorithm (Clarkson et al., 2012) was used to pick the optimal calibration points and produce the requisite transformation matrices which deliver the lowest post calibration RMS point re-projection errors.

The complete calibration process (including data collection and processing) took approximately nine minutes in total. It is important to note this calibration procedure is not required for every scan. Providing the Kinects® are left in the same position and not allowed to move, the same calibration parameters could be applied to many scans collected within a single data collection session.

Test Objects

Cylinders representing common body segments (table 1, figure 3) were manufactured from solid aluminium section using a V290 centre lathe (Harrison Colchester, Heckmondwike, UK). Cylinders were used in this study for a number of reasons (based on the rationale of the National Physical Laboratory's Phantom Man): geometric shapes can be measured reliably and accurately using standard tools used in metrology. Cylinders (of an appropriate size) could be manufactured in-house using machine tools accurate to 0.1 mm. These objects allow us to assess the agreement of measurement compared to a highly accurate ground truth. Static objects eliminate the potential for motion artefact in the 3D scans, reducing the possibility of external influential parameters, and thereby enabling a reliable assessment of the system's fundamental operating characteristics.

This study was part of a wider project concerning the validation of our scanning system – absolute accuracy of the system was a primary concern. While a mannequin could be used to compare our system to measurement tools such as callipers and tape measure, a 'true' value of segment girth and volume might only be obtained by using a commercial, high specification scanner. However, comparing scanning systems directly makes it very difficult to isolate common, shared sources of uncertainty such as calibration quality, scanning angles, light levels etc. As such, a 'calibrated measurement artefact' allows objective evaluation. Comparing a scanning system to a scanning system is cited in the literature as bad practice (Robinson et al., 2012).

chosen for this study as they allow gold standard measurements to be obtained using standard measurement equipment, and do not rely upon another scanner for validation, cited in the literature as bad practice (Robinson et al. 2012). The static objects also eliminate the potential for motion artefact in the 3D scans, reducing the possibility of external influential parameters, and thereby enabling a reliable assessment of the system's fundamental operating characteristics.

ADD PC SPECS AROUND HERE!
Figure 2 near here

A uniform coating of satin black spray paint was applied around the ends of each cylinder. After curing, the black paint was covered with a single layer of masking tape. The cylinders were placed on a measurement table and a DHG-300 vertical height gauge (Baty, Sussex, UK) - accurate to ± 0.01 mm – used to cut the tape at a consistent height of 25 mm from the table top. After removing the offcut tape, a uniform coating of white powder was applied to the cylinders, providing a non-reflective surface for scanning. The remaining tape was removed, leaving a black band at either end of the cylinders (figure 3). The white area in between the black bands defined a region of interest, which could later be identified and segmented from the colour rendered scans.

Each cylinder's region of interest was measured by a single skilled engineer using a pair of calibrated engineer's digital callipers (Kennedy, Leicester, UK), accurate to ± 0.01 mm. Length and diameter measurements were obtained, enabling calculation of gold standard girth values and object classification based on ISO 20685-1 (International Standards Office, 2010).

Table 1 near here

Data Capture and Post Processing

The cylinders were scanned in five different positions within the capture volume (figure 2), representing the centre and extremes of the calibrated footprint. Each cylinder was raised from the scanning surface and approximately centred within the vertical field of view. This allowed the

effectiveness of the device specific calibration to be assessed, as previous research has shown this region to exhibit the greatest errors (Clarkson et al., 2013).

Figure 3 near here

The system was setup and calibrated four times. For each calibration, the cylinders were scanned once in each of the five positions. Each scan took ~1 second, due to the delay in turning on and off each Kinect's® IR projector. Simultaneous 3D and RGB colour data were captured by the system, and used in conjunction with the requisite transformation matrices and the Kinect's® integral coordinate transformation functions to produce 360° coloured point cloud scans of each cylinder.

Observation of the point cloud scans revealed the Kinect® struggled to resolve surfaces at high depth gradients. Algorithms based on the MATLAB programming language (Mathworks, Cambridge, UK) were used to remove these areas.

A single operator manually digitised three points on the upper and lower black/white interfaces using a 3D point cloud viewer within a bespoke software application. These points were used to create three dimensional segmentation planes, identifying the upper and lower limits of the region of interest. Data processing scripts based on the MATLAB programming language were used to create parallel segmentation planes throughout the length of the region of interest. The segmentation planes were separated by a distance of 10 mm, enabling assessment of random measurement variation throughout the length of the cylinders, due to factors such as distortion of the depth data (Clarkson et al., 2013). The 10 mm 'slice height' was a compromise between slices small enough to represent measurement variation, whilst large enough to avoid being susceptible to measurement noise. Points in-between the segmentation planes were identified, splitting up the scan into 3D point cloud 'slices', figure 4a. Each slice was 'collapsed', creating a 2D topological representation of the cylinder's outer surface, shown as the ~~black~~ points in figure 4b. A cubic smoothing spline (de Boor, 2001) ($\rho = 0.79$) was fitted to the 2D point data, smoothing random noise in the points representing the cylinder's outer surface, shown as the grey line in figure 4b. The smoothing spline created a continuous line representing a smoothed average of the scan's data points, including noise in the scan and overlapping points in the regions of the scan visible to multiple scanners. The length of the fitted spline was then calculated by assessing the spline at discrete points along its length (360 in total), given as the ~~creating 'virtual' points throughout the spline and~~ ~~calculating the~~ summed Euclidian point to point distance of all the points. This distance was used as the measurement~~, estimating~~ of the cylinder's girth within a particular slice. This process was repeated for each slice, producing a series of girth measurements at 10 mm intervals throughout the length of the cylinders~~. This process took~~, taking around 15 seconds per cylinder. For the purposes of this study a repeatable, prescribed measurement protocol was developed. However, the scanning system is capable of taking measurements at any position along the cylinder's length (and at any angle). For this study, each measurement was an average of 3D points within 10 mm of the measurement line. This averaging distance can be reduced but the number of points within each slice is reduced – affecting the integrity of the measurement.

Figure 4 near here
MODIFY FIGURE 6b TO SHOW OVERLAP CHANGE TO CIRCLE BASES
HOW MANY DISCRETE POINTS ALONG THE SPLINE? INCLUDED IN THE DESCRIPTION

Data Analysis

The 'slices' of point data were 10 mm wide in all cases. Differences in cylinder length meant that differing numbers of slices were created during scanning. To account for ~~differences in cylinder length~~this, ten point slices equally spread throughout the region of interest were considered as the girth measurements of each cylinder (see figure 4).

Mean absolute reliability was calculated by comparing girth measurements from the system to the gold standard manual measures, enabling comparison to ISO 20685-1.

Relative technical error of measurement (TEM) was calculated using the method shown in Perini et al (2005), enabling comparison to ISAK standards. Average relative intra-tester TEM was calculated for the 10 girth measurements per cylinder across the five positions and four calibrations, with the average value reported. Similarly, the relative inter-tester TEM was calculated by comparing all the measurements for a given cylinder to the gold standard manual measurement.

Results

Accuracy was comparable across the four cylinders (table 2), with the results showing the scanning system to consistently overestimate girth.

Figure 5 near here

Figure 5 shows the errors in girth measurements for each 'slice' created along the height of the cylinder. The overestimation is apparent at all levels and the standard deviation of error is similar within each cylinder. Standard deviation within each slice (over all repeats) and across slices decreases as cylinder size increases.
INCLUDE GIRTH MEASUREMENT ALONG THE LENGTH

Reliability throughout the length of all four cylinders was also comparable, table 2. Reliability was slightly higher in the two larger cylinders, represented by a lower inter-tester TEM, a lower 95% confidence interval, and lower standard deviations. However, a Kendall's tau test ($\tau = 0.112$, $p < 0.05$) showed a lack of interaction between cylinder girth and girth error.

Table 2 near here

Girth measurements of cylinders 3 and 4 met the requirements of the ISO 20685-1 standard (large girth, 95% confidence interval of ± 8 mm (International Standards Office, 2010)), whereas cylinders 1 and 2 did not (small girth, 95% confidence interval of ± 4 mm (International Standards Office, 2010)).

ISAK define two measurement pro-formas: a restricted pro-forma comprising 13 measurements (including 5 girths) and a full pro-forma comprising 42 measurements (including 13 girths) (Stewart and Sutton, 2012). ISAK accredited practitioners are required to meet TEM scores dependent upon their level of accreditation. Level 1 practitioners are trained in taking the restricted measurement pro-forma, and are required to demonstrate an inter-tester TEM of < 2.5% and intra-tester TEM of < 2% at examination, with the intra-tester TEM falling to < 1.5% post examination. Similarly, level 2 practitioners are trained in taking the full measurement pro forma, and are required to demonstrate an inter-tester TEM < 12% and intra-tester TEM of < 1.5% at examination, with the intra-tester TEM falling to < 1% post examination. Inter-tester TEM is assessed by comparing measurements from level 1 and 2 practitioners to those obtained by an ISAK level 3 criterion practitioner, considered to obtain 'true' values (Stewart and Sutton, 2012).

Results show the scanning system to meet both inter and intra tester post-examination TEM requirements for an ISAK level 1 practitioner in all four cylinders. Inter and intra tester post-examination TEM requirements of a level 2 practitioner were met in the largest cylinder only (cylinder 4).

Discussion

The aim of this study was to determine whether a 3D body scanning system based upon four depth cameras was capable of meeting ISAK and ISO standards for body segment girth measurements.

Scan-derived girth measurements were shown to comply with ISO standards for larger body segments - such as the torso and upper legs – but to be non-compliant when scanning smaller segments, such as

the lower arms. Scan-derived girth measurements were shown to meet the requirements of a level 1 ISAK practitioner in all four cylinders, and the requirements of a level 2 practitioner in the largest cylinder only. However, it is important to note the conclusions drawn from this study relate to a relatively small sample size of girth measurements only: forming a small part of the ISAK measurement pro-forma. Further studies with larger cohorts of living human participants are required to verify the system is able to adhere to ISO and ISAK standards across the range of measurements included in the ISO and ISAK measurement pro-formas, covering a variety of body segments.

Importantly, girth measurements showed a lack of proportional bias between the four cylinders. Instead, presence of a fixed measurement bias was identified, which could be easily corrected with a simple offset factor.

The standard deviation of measurement decreased as the s-ize of the cylinder increased. This may be due to the nature of the Kinect scanning system and its ability to resolve larger objects more reliably. While the size of the objects used in this study are within ISAK standard, there may be implications for scanning smaller objects or body segments.

The system has been described so far as 'low cost', referring to the price of the scanning hardware (around £150). This study, however, used commercial software for the purposes of analysis of the data which would add to the cost of any potential system. The elements of the analysis which relied upon MATLAB have – at the time of writing – been incorporated into the main, bespoke software system. It is anticipated that this software will form an integral part of any scanning system. While our software is not commercially available, it has been developed with the intention of being used as part of a low cost scanning system. As such it may be made available at low cost (several hundred pounds).

Adherence to post examination requirements of an ISAK level 1 practitioner, combined with the system's low cost, simplicity, ease of use, and quick scanning time, suggests such a system is likely to be well received by the kinanthropometry community. However, this would be subject to the results of the additional studies highlighted above demonstrating comparable performance. A system such as this could foreseeably be installed within research laboratories or gyms and used for a variety of anthropometric assessment activities. The ability to quickly collect scans suggests that repeated scans of athletes could be collected within training environments to monitor changes in physique over time, without being prohibitive to normal activities. Significant applications also lie within talent assessment activities, as large numbers of people could be quickly scanned and their anthropometric characteristics assessed via automated data analysis algorithms. The scans can also be archived, and reviewed or additional measurements taken at any point in the future.

TEM and standard deviation was shown to decrease with an increasing cylinder diameter. One possible explanation is that the Kinect[®] struggles to accurately resolve the surface of small objects, or objects with surfaces having high incidence angles, resulting in increased noise in the 3D scans. Another explanation is that as cylinder diameter decreases the physical distance which the cylinder must be moved when moving between positions within the capture volume is increased, leading to greater potential for inter scan variability. Such variability can be reduced within the application of body scanning by requesting participants stand on markings on the floor, ensuring they stand in the same position within the capture volume across repeated scans.

Cylinder shaped objects were chosen for this study, allowing gold standard measurements to be obtained using first principle modelling, and reducing the effects of external influential factors: enabling an accurate assessment of the system's fundamental operating characteristics. The cylinders were manufactured to be dimensionally similar to common body segments (International Standards Office, 2010; Robinson et al., 2012), but their simple shape means they lack the complex curves and contours typical of the human body. Furthermore the surface of the cylinders was optically 'ideal', providing a non-reflective and non-attenuating surface for scanning. In contrast, the human body may attenuate or reflect some of the invisible light used by the Kinect's[®] 3D vision system, resulting in

noise and measurement errors. Further investigations with human participants are therefore required to determine equivalent performance when scanning real body segments of greater complexity.

The use of static objects eliminated the potential for motion artefact in the 3D scans. However, involuntary movement of the human body during scanning is highly likely, despite the system's short scanning duration (~1 second). Such movement would increase measurement errors, and hence TEM. In addition, the cylinder was scanned in isolation. When scanning human participants there is a risk of occlusion (from arms and legs). This can be accounted for by careful positioning of the participant by, for example, lifting a leg or arm away from the segment of interest. F—Further investigations with human participants are therefore required, using simple techniques such as light touch (Kouzaki and Masani, 2008; Lackner, Rabin, and DiZio, 2001), visual focus upon a fixed target (Paulus, Straube, and Brandt, 1984; Vuillerme and Nafati, 2007), and hand holds to minimise involuntary postural sway and assessing body position to minimise occlusion.

For the purposes of this study, the calibrated capture volume was kept as small as possible: large enough to contain a typical human body segment, but small enough so the objects being scanned are as close to the Kinects as possible, resulting in greater accuracy (K Khoshelham, 2010). For applications focussing upon maximum accuracy of measurements from only one or two segments, then the same setup could be used. For applications focussing on whole body measurements, then it would be desirable to obtain whole body 3D scans in one data capture operation. The system presented here could be expanded to cover a larger capture volume or include additional sensors, increasing the scanning field of view. In this case, further studies would be required to determine equivalent performance.

The majority of the method demonstrated within this study would remain the same should human body segments be scanned, with the only change concerning the area of segmentation and landmark identification. Firstly, it is important to note the need to digitise three points and form repeated segmentation planes is not necessary to simply obtain a single girth measurement. This method was only developed for the purposes of this study. Instead, the location of a girth measurement could be identified with a single reference point, assuming a segment or body coordinate system has first been defined. Secondly, the landmark identification and digitisation process would differ significantly. In a similar manner, anatomical landmarks could be manually palpated on the body and identified using small coloured markers (one marker per landmark), enabling subsequent digitisation and segmentation. However, this is likely to be a very time consuming process. Alternatively, anatomical landmarks may simply be identified and digitised by visually inspecting the colour rendered 3D scans, eliminating the need for palpation of the body. Other techniques include automatic landmark identification algorithms, considerably reducing the required post processing time. The adopted landmark identification technique is likely to depend upon the required level of accuracy, ostensibly, manual landmark palpation, marking, and digitisation is likely to yield the greatest accuracy.

The system presented here offers significantly shorter data capture and processing times when compared to other systems published in the literature. The system calibration process takes < 9 minutes, which subsequently enables many scans to be collected assuming the Kinects® are left in place. Each scan takes approximately 1 second, plus a further 2 seconds to perform the necessary post processing steps, 3D reconstruction, and save the scan file. Whilst only girth measurements are presented here — forming a small part of the whole ISAK measurement pro forma — the scans collected by the system could be used to take the majority of measurements could be used to obtain the fullwithin the ISAK measurement pro-forma, expected to take < 25 seconds in total, based upon findings from this study.. A significant benefit of a scanning system such as this is that each captured scan contains a large amount of information, measurements can be taken in absence of the participant and more complex measures such as area and volume can be extracted (see below). Longitudinal studies examining changes in shape can be conducted, providing more information than is currently possible with traditional measurement techniques.

The greatest challenge in developing these systems is their ability to identify anatomical landmarks. Without it, accurate location may only be possible using manual palpation and identification (with a prominent marker for example). Without this ability, potential time savings are negated by the need for manual intervention. However, other potential benefits (the time commitment for the participant is considerably reduced), could provide many advantages within sports training and competition environments. ~~Importantly, this negates any time for landmark identification, which is dependent upon the method adopted, as discussed above. Nevertheless, the time commitment for the participant is considerably reduced, offering many advantages within sports training and competition environments.~~

Although not considered as part of this study, the person specific 3D scans hold great potential for a wealth of ~~greater complexity~~ measurements of greater complexity (Schranz et al., 2010; Schranz, Tomkinson, Olds, Petkov, and Hahn, 2012). For example, body segment parameters (BSPs) could be automatically estimated from the 3D scan data (Clarkson et al., 2012; Clarkson, Wheat, Heller, and Choppin, 2014; Wheat, Hart, Domone, and Outram, 2011). Currently this is a very time consuming and complicated process, requiring many manual measurements of the human body, and prone to significant errors due to significant assumptions and the use of generic models (Clarkson et al., 2014).

~~Conclusions~~Summary

A low cost 3D scanning system – based upon four depth cameras - was developed, capable of scanning body segments and calculating girth measurements. Cylinders representing common body segments were scanned with the system, and calculated girth measurements compared to gold standard data.

Scan-derived girth measurements met the requirements of an ISAK level 1 practitioner (intra-tester TEM < 1.5%, and inter-tester TEM < 2.5%) in all four cylinders, and the requirements of a level 2 practitioner (intra and inter-tester TEM < 1%) in the largest cylinder only. ISO standards for scan-derived girth measurements were met in the two larger cylinders only (large girth, 95% confidence interval of ± 8 mm). A fixed measurement bias was identified in the system, which could easily be corrected with a simple offset factor. Further work is focussed on studies involving a large cohort (~40) of living participants to verify comparable performance across all of the measurements included in the ISO and ISAK measurement pro-formas.

The system offers many advantages over existing techniques: significantly reducing time required with the participant (~1 second scan time, plus any palpation time), offering the ability to take and review measurements long after the original scan, and providing the potential to calculate greater complexity measurements.

This work represents a first step in the process of high quality, low cost body scanners becoming a reality. The findings of this initial study, combined with the system's low cost, ease of use, and additional features, suggests such a system is likely to be well received by the kinanthropometry community. Further studies involving living human participants and a wider range of measurements are however required before such a system could be widely accepted. A system such as this could foreseeably be installed within laboratory and training environments, having many applications for morphologic profiling or monitoring within elite sport training environments and talent assessment programs, with possibility for a range of additional functionality. In the future, it is likely that sensors will improve, increasing the accuracy and desirability of this technology.

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Table 1, Cylinders representing common body segments

Cylinder	Representative Segment	ROI Length (mm)	Diameter (mm)	Girth (mm)	ISO 20685-1 Girth Category
1	Lower arm	271.83	88.06	276.65	Small
2	Upper arm and Lower leg	373.81	113.13	355.41	Small
3	Upper leg	373.45	161.97	508.84	Large
4	Torso	350.40	227.08	713.39	Large

Table 2, Reliability and accuracy of girth measurements

Measure	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Mean Scan-Derived Girth (mm)	284 (4)	363 (4)	516 (3)	722 (2)
Mean Scan-Derived Girth Error (mm)	7 (4)	~~7~~ 8 (4)	7 (3)	9 (2)
95% Confidence Interval (mm)	±8	±8	±6	±5

Average Relative Intra-Tester TEM (%)	1.05 (0.44)	0.82 (0.38)	0.42 (0.18)	0.28 (0.12)
Relative Inter-Tester TEM (%)	2.08	1.71	1.04	0.92

Where appropriate, numbers shown in brackets represent corresponding standard deviation values.

<u>Figure Captions</u>

Figure 1, The system calibration process
        a) Calibration rig
        b) Depth image
        c) Edge filtered image
        d) 2D Sphere centres located via Hough Transforms
        e) Located 3D centres
Figure 2, The five scanning positions and arrangement of Kinects[®] outside the capture volume
Figure 3, Cylinders representing common body segments
Figure 4, The point cloud segmentation and girth calculation process

a) The cylinder scans split up into 3D point 'slices'Each cylinder was split up into 10 mm slices, 3D points contained within each slice were taken as a single measurement. Ten evenly spaced slices were taken from each cylinder to account for differing lengths (illustrated here with solid circles).

b) A point 'slice' converted to a 2D topological representation with fitted smoothing spline3D point data from each slice was represented by a smoothing spline. This permitted areas of overlapping point data in areas covered by multiple scanners.

b) Figure 5, The errors in girth measurement for each 'slice' created from the 3D scan. Error bars represent the standard deviation of error at each slice level over all repeats.

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