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Reliability of the Styku 3D Whole Body Scanner for the Assessment of Body Size in College Athletes

by

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Bachelor of Science, University of North Dakota 2014

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for the degree of

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This thesis, submitted by Joseph DeRouchey in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Dr John Fitzgerald

Dr Grant Tomkinson

Dr Jesse Rhoades

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

Grant McGimpsey
Dean of the School of Graduate Studies

December 6, 2018
Date

PERMISSION

Title	Reliability of the Styku 3D Whole Body Scanner for the Assessment of Body Size in College Athletes
Department	Kinesiology
Degree	Master of Science

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Joseph DeRouchey

November 30th, 2018

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ABSTRACT

3-dimensional (3D) anthropometry, such as volumes and surface area, is important for predicting sport performance and assessing health status, but most commercially available whole body scanners are cost prohibitive. The aim of this study was to determine the test-retest reliability of a commercially available single-camera 3D body scanning system (Styku S100) to assess whole body and circumferences, and whole-body and segmental surface areas and volumes of apparently healthy university students. Forty-nine (19 male) physically active students from a Division I university were scanned and measurements were analyzed. Reliability was quantified as the systematic error, random error, and test-retest correlation. The Styku scanner demonstrated nearly perfect reliability. Systematic errors were negligible (mean standardized bias [95%CI]: within-session, 0.04 [0.02, 0.06]; between-session, 0.02 [0.01, 0.03]), random errors were negligible (mean standardized typical error [95%CI]); within-session, 0.14 [0.11, 0.17]; between-session, 0.09 [0.07, 0.13]), and test-retest correlations were nearly perfect (mean ICC [95%CI]: within-session, 0.98 [0.97, 0.99]; between-session, 0.99 [0.99, 1.00]). 3D scanning using a single-camera system may be a good tool for health and fitness professionals looking for a low-cost system to evaluate human body size and shape.

Chapter 1

INTRODUCTION

Researchers, interested in sport performance and health, have used anthropometry — the surface measurement of skinfolds, lengths, breadths, and circumferences of the human body — for decades (Kerr, Ackland, & Schreiner, 1995). Direct anthropometric assessment (e.g., through the use of skinfold calipers, circumference tapes, bone calipers) has been widely used for some time due to the low cost and maintenance of equipment. However, this approach is invasive, requires a high initial investment of training for proficiency, and is unable to directly measure whole and segmental body surface areas and volumes (Kuehnapfel, Ahnert, Loeffler, & Scholz, 2017). Advancements in anthropometry, such as 3-dimensional (3D) body scanning, have sped up and simplified anthropomertic assessment (Bragança, Arezes, Carvalho, & Ashdown, 2016), considerably reducing the participant burden and tester training. Additionally, 3D scanning is less invasive as there is no need for physical contact and particiapnts can be scanned without being viewed by testers.

3D body scanners, in addition to the measurement of traditional 1D measures, has also been used to quantify 2D and 3D measures such as limb volumes and surface areas, cross-sectional areas, and corresponding asymmetries (Ng, Hinton, Fan, Kanaya,& Shepherd, 2016; Rauter, Vodicar & Simenko, 2017). Anthropometric measures can be used to assess sports performance (Brocherie, Girard, Forchino, Al Haddad, Dos Santos, & Millet, 2014), track changes in body size and shape throughout an athlete's season (Prokop, Reid, & Andersen, 2016), and inform important decisions related to rehabilitation (Kordi, Haralabidis, Huby, Barratt, Howatson, & Wheat, 2018). 3D scanners provide professionals the ability to track data longitudinally over large sample sizes quickly and less invasively compared to traditional methods (Schranz et al., 2010; 2012). Interestingly, 2D (e.g., cross-scetional areas) and 3D (e.g., volumes and surface areas) measures are generally better predictors of sporting success than are 1D measures (e.g., lengths, girhts, breadths). In the health field, 3D body scanning has made it easier to quantify abdominal cross-sectional areas and volumes, which are meaningful predictors of diabetes and cardiovascular disease risk, and quantify longitudinal changes in body composition (e.g., in response to dietary and/or exercise interventions) (Lin, Chiou, Weng, Fang, & Liu, 2004).

In recent years, the cost of 3D scanners has significantly decreased in response to an increased demand and advances in scanning technology. While top-line laser scanners such as the *Vitus Smart XXL* currently cost over US$65 k, less expensive multi-camera systems using structured light are commercially available for ~US$10 k excluding software and service expenses (Daanen, & Ter Haar, 2013). While it appears that multi-camera Microsoft Kinect-based systems can collect reasonably accurate and reliable anthropometric measurements (Bullas et al., 2016; Clarkson et al., 2016), there are currently no data on less expensive single-camera systems such as the Styku S100 system. With the aid of a 360° rotating platform, single-camera systems appear capable of achieving similar precision to multi-camera systems, making 3D anthropometry more applicable to coaches, researchers, and clinicians.

The aim of this study was to determine the test-retest reliability of a commercially available single-camera 3D body scanning system (Styku S100) to assess circumferences, and whole-body and segmental surface areas and volumes of apparently healthy college sudents. Reliability data were compared to international error standards recommended by the International Society for the Advancement of Kinanthropometry (i.e., typical error [TE] ≤1.5%) as a reference (Stewart, Marfell-Jones, Olds,& de Ridder, 2011). It was hypothesized that a single-camera 3D system would demonstrate very small errors that are comparable to those observed in manual anthropometry.

Chapter 2

METHOD

Experimental Approach to the Problem

The aim of this study was to quantify the test-retest reliability (henceforth termed "reliability") of the Styku S100 3D whole body scanner for the measurement of human body size (circumferences, surface areas, and volumes). During a single visit to the University of North Dakota's Human Performance Laboratory, participants were scanned six times (two clusters of three scans) with a 5-minute break between the two clusters as to create two separate testing sessions. Systematic (bias) error, random (within-subject) error, and test-retest correlation were used to quantify measurement reliability. A Level 1 accredited anthropometrist should be able to measure circumferences, lengths, and breadths with a technical error of measurement (TEM) of ≤1.5% (Stewart et al., 2011). This international standard was used as the criterion-referenced threshold.

Participants

Forty-nine (mean±SD: age, 22.7±3.3 years; height, 174±8 kg; mass, 75±14 kg; BMI, 24.4±3.4 kg/m^2) students were recruited from a large midwest university. Participants were excluded from the study if they were injured, had casts or braces appended to their body, or were unable able to stand on a raised rotating platform. All testing procedures were approved by the University of North Dakota Institutional Review Board.

Procedures

After providing written consent, participants changed into form fitting underwear (briefs for men and briefs plus sports bra for women) and had their height measured with a stadiometer (Seca, Chino, CA) to the nearest 0.1 cm and their mass measured with a digital scale (Detecto, Webb City, MO) to the nearest 0.1 kg. Participants were ushered to the scanning area where they were scanned using a Styku 3D S100 whole body scanner, which was configured using manufacturer specifications (Figure 1). This 3D scanner comprised a turntable, a Microsoft Kinect V2 camera (Microsoft Corporation, Redmond, WA) enclosed in a lightweight aluminum stand, and the MyBodee measurement extraction software (Styku, Los Angeles, CA). Participants were asked to step onto the turntable and assume a standard scanning pose, where they stood still, with their feet on the marked foot prints, arms abducted ~45°, hands closed into a fist, head in a horizontal plane, whilst they breathed normally and the turntable rotated 360° for a duration of ~20 seconds. During this time, the scanning stand comprising the Kinect camera system projected a structured light pattern onto the participant, with the reflections captured as millions of Cartesian coordinates. The MyBodee software used recognition technology to automatically locate surface landmarks that were used to extract circumferences, and whole-body and segmental surface areas and volumes.

Triplicate scans were made of each participant with minimal time in-between in order to reduce biological error that might have arisen from resetting the standard scanning pose. Participants then stepped off the turntable, rested in a standing/seated position for 5 minutes whilst the scanner was recalibrated, before they were again scanned in triplicate.

Statistical Analysis

Within-session reliability was examined by comparing scans 1–3 and between-session reliability by comparing the means of scans 1–3 and scans 4–6. Descriptive statistics were presented as means and standard deviations. Systematic error was quantified as the absolute and standardized difference in means; random error as the absolute, percent and standardized typical error; and test-retest correlation as the intra-class correlation coefficient (ICC). All calculations performed using a publically available reliability calculator (Hopkins, 2007). To interpret the magnitude of bias and typical error, standardized effect sizes (ES) of 0.2, 0.5 and 0.8 were used as thresholds for small, moderate and large respectively, with ES<0.2 considered to be negligible. To interpret the magnitude of correlation, ES of 0.1, 0.3, 0.5, 0.7 and 0.9 were used as thresholds for low, moderate, high, very high and nearly perfect respectively, with ES<0.1 considered to be negligible. Ninety-five percent confidence intervals (95%CI) were calculated for all variables.

Chapter 3

RESULTS

Within-session reliability

The Styku 3D scanner demonstrated nearly perfect within-session reliability. Systematic errors were negligible (mean standardized bias [95%CI]: 0.05 [0.03, 0.07]), random errors were negligible (mean typical error [95%CI]); percent, 1.7 [1.2, 2.2]; standardized, 0.14 [0.11, 0.17]) with more than half of the measures (59%) demonstrating acceptable random error compared to international standards, and test-retest correlations were nearly perfect (mean ICC [95%CI]: 0.98 [0.97, 0.99]) (Table 1). Differences in mean systematic errors, random errors, and test-retest correlations between body dimension types (circumferences, surface areas, and volumes) were negligible.

Between-session reliability

The Styku 3D whole body scanner demonstrated nearly perfect between-session reliability. Systematic errors were negligible (mean standardized bias [95%CI]: 0.02 [0.01, 0.03]), random errors were negligible (mean typical error [95%CI]); percent, 1.0 [0.7, 1.3]; standardized, 0.09 [0.07, 0.11]) with most measures (82%) demonstrating acceptable random error compared to international standards, and test-retest correlations were nearly perfect (mean ICC [95%CI]: 0.99 [0.99, 1.00]) (Table 2). Differences in mean systematic errors, random errors, and test-retest correlations between body dimension types (circumferences, surface areas, and volumes) were negligible. The differences between within-session and between-session typical errors (e.g., within-session mid-thigh circumference vs. between-session mid-thigh circumference) were negligible, yet statistically significant for 15 of 22 measures.

Chapter 4

DISCUSSION

The aim of this study was to determine the reliability of a commercially available single-camera 3D body scanning system. Negligible within- and between-session systematic and random errors, and nearly perfect test-retest correlations, were observed, with more than half of the within-session and most of the between-session randoms errors considered “acceptable” relative to international error standards. While no significant differences were found between the average random errors for circumferences, surface areas, and volumes between within- and between-session data, when looking at the individual measurements, 15 of the 22 measurements showed significant differences when evaluating confidence intervals. This indicates that researchers looking for the most precise measuring procedure should take three scans and use the average for their measurement. Between session standardized TEs for circumferences, surface areas and volumes (0.10±0.04, 0.09±0.04, and 0.07±0.05 respectively) were trivial and therefore can identify trivial differences between individuals.

Previous studies examining the capabilities of the Microsoft Kinect to take circumference and volume measurements observed similar results to the present study, %TE range: 0.28-2.0 for circumference measurements (Bullas et al., 2016; Clarkson et al., 2016).

Together these findings suggest that whole body scanners using multi-camera and single-camera systems are capable of taking reliable measurements that were previously difficult to obtain, such as total body volumes and surface areas. It is important to note the previous studies combined the data collected by 4 depth cameras positioned equidistant around the scanned object. To our knowledge, the present study is the first to evaluate the reliability of a 3D whole body scanner to take 2D anthropometric measurements such as circumferences as well as 3D anthropometric measurements (surface areas and volumes) using a single-camera system.

The results of this study suggest 3-D body scanning using a single-camera system may be a good fit for coaches, practitioners and scientists looking for a low cost automated system for the evaluation of body shape and size. 3D scanners provide an efficient way to assess limb volumes (which are strong predictors of sprint performance) (Hermassi, S., Schwesig, R., Wollny, R., Fieseler, G., Van Den Tillaar, R., Fernandez-Fernandez, J., Chelly, M., 2017), limb surface areas (proportional to strength) (Ng, B. K. et al., 2016) and evaluate asymmetries between limbs (Rauter, S., Vodicar, J., & Simenko, J., 2017). Professionals can use this technology to quickly measure large samples, such as sports teams, without the invasiveness of manual measurement methods (Schranz et al., 2010). 3D whole body scanners have been used to identify body composition variables that fluctuate during a competitive season, which could help strength coaches optimize/maintain speed, agility, strength, endurance, and mobility depending requirements of in- and off-season demands (Prokop, N., Reid, R., & Andersen, R., 2016). It has also been used to identify key 3D anthropometric traits specific to sport success that would have otherwise been difficult to obtain (Schranz et al., 2010; 2012). Paired with an assessment of site-specific fatness, sport professionals may be able to evaluate the relationship between lean musculoskeletal limb volumes and exercise performance similar to DXA, which may provide useful information about musculoskeletal functioning after injury (Raymond-Pope, C., Dengel, D., Fitzgerald, J., & Bosch, T., 2018). Health professionals could also use this technology to better assess health risks related to body composition by quantifying abdominal cross-sections and volumes (Bigaard et al., 2005; Lin, Chiou, Weng, Fang, & Liu, 2004), and tracking the success of exercise and dietary interventions (Ning et al., 2014).

A number of limitations were present in this study, first the lack of hand holds for participants on the turntable likely increased error of measurement due to postural sway. To reduce TEs, some type of support system may be added to reduce error caused by sway. Furthermore, the scanning system used in this study required a specific body position be maintained throughout the twenty second scan, specifically that the arms maintain a forty-five-degree separation laterally from the torso. This position may have been difficult to maintain during the scan as well as replicate between scans. Secondly, participants in this study were primarily individuals predisposed to competitive sports and therefore were a homogenous sample with little diversity in body composition. Lastly, no validity data was evaluated in the present study, though a previous study by (Bullas et al., 2016) observed a 6% systematical overestimation of thigh volume when a multi-camera system was compared to a previously validated high precision 3D surface imaging system (3dMD). Future studies will be required to identify the accuracy of single-camera whole body scanners.

In conclusion, the commercially available single-camera system used in this study is highly repeatable, capable of identifying trivial changes for most measurements and exceeded ISAK standards of typical error when measuring circumferences. This, in addition to its portability, low cost, low invasiveness, and time efficiency make this measurement tool a viable alternative to other cost prohibitive scanners and manual measurement methods.

Chapter 5

PRACTICAL APPLICATION

The results of this study suggest 3-D body scanning using a single-camera system may be a good fit for coaches, practitioners and scientists looking for a low cost automated system for the evaluation of body shape and size. This technology would offer athletic professionals and clinician's accessible anthropometric data that was previously laborious to extract for larger cohorts (Schranz et al., 2010). Understanding how body shape and size fluctuates, and potential variables that may influence the fluctuation within individuals can help coaches and physicians tailor their team or patients' training, nutrition, lifestyle, and informative resources to further support their objective (Prokop et al., 2016). Our reliability data can be used to determine margins of confidence when assessing worthwhile change over the course of an athletic season or exercise intervention. For example, to determine if real or meaningful changes in thigh circumference have occurred between certain time points of an athlete's season, coaches can multiply the %TE provided in this study by 1.5–2.0 (Hopkins, Will G., 2010). For example, by multiplying the percent TE (0.6%) by 1.5 we can determine that 0.9% change is needed to be sure real change has occurred. The percent change (0.9%) can be multiplied by the circumference measurement taken by the whole body scanner (e.g., 56.4 cm), and we can determine that 0.5 cm of growth must occur before we can be sure that real change has occurred.

Tables

Table 1. Within-session reliability data.

	Scan 1	Scan 2	Scan 3					
Measurement	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**Bias (95%CI)**	**Standardized bias (95%CI)**	**Percent TE (95%CI)**	**Standardized TE (95%CI)**	**ICC (95%CI)**
Lower Bicep Circumference (cm)	26.1 (3.1)	26.4 (2.9)	26.4 (3.1)	0.25 (−0.05, 0.54)	0.09 (−0.02, 0.19)	2.8 (2.4, 3.5)	0.26 (0.21, 0.32)	0.94 (0.90, 0.97)
Forearm Circumference (cm)	25.8 (2.8)	26.0 (2.9)	26.0 (2.9)	0.24 (−0.03, 0.52)	0.09 (−0.01, 0.19)	2.8 (2.3, 3.5)	0.25 (0.21, 0.19)	0.94 (0.90, 0.97)
Arm Surface Area (cm^2)	1232 (1.2)	1246 (1.2)	1239 (1.2)	14 (−4, 32)	0.07 (−0.02, 0.16)	3.7 (3.1, 4.6)	0.23 (0.19, 0.29)	0.95 (0.92, 0.97)
Calf Circumference (cm)	35.1 (2.4)	35.4 (2.3)	35.3 (2.4)	0.27 (0.08, 0.46)	0.12 (0.03, 0.20)	1.4 (1.2, 1.7)	0.21 (0.18, 0.26)	0.96 (0.93, 0.98)
Lower Thigh Circumference (cm)	42.9 (3.0)	43.2 (3.1)	43.1 (3.0)	0.33 (0.12, 0.53)	0.11 (0.04, 0.18)	1.2 (1.0, 1.5)	0.18 (0.15, 0.22)	0.97 (0.95, 0.98)
Upper Bicep Circumference (cm)	28.6 (3.7)	28.9 (3.7)	28.9 (3.7)	0.28 (0.02, 0.54)	0.08 (0.55, 0.81)	2.4 (2.0, 3.0)	0.19 (0.16, 0.23)	0.97 (0.95, 0.98)
Leg Surface Area (cm^2)	2235 (1.1)	2247 (1.1)	2245 (1.1)	11 (−3, 24)	0.06 (−0.01, 0.13)	1.5 (1.3, 1.1)	0.17 (0.14, 0.21)	0.97 (0.95, 0.98)
Arm Volume (cm^3)	2166 (1.3)	2197 (1.3)	2210 (1.4)	30 (−12, 72)	0.05 (−0.02, 0.12)	4.8 (4.0, 6.0)	0.17 (0.14, 0.21)	0.97 (0.95, 0.98)
Leg Volume (cm^3)	6131 (1.2)	6184 (1.2)	6169 (1.2)	54 (−2, 109)	0.06 (0.00, 0.13)	2.3 (1.9, 2.9)	0.16 (0.13, 0.20)	0.98 (0.96, 0.99)
Torso Volume (cm^3)	37907 (1.2)	38176 (1.2)	38164 (1.2)	246 (−187, 680)	0.04 (−0.03, 0.10)	3.3 (2.7, 4.1)	0.16 (0.13, 0.20)	0.98 (0.96, 0.99)
Mid-Thigh Circumference (cm)	56.4 (4.1)	56.4 (4.2)	56.3 (4.3)	0.18 (−0.05, 0.41)	0.04 (−0.01, 0.10)	1.0 (0.9, 1.3)	0.14 (0.12, 0.17)	0.98 (0.97, 0.99)
Neck Circumference (cm)	34.1 (3.9)	34.2 (4.0)	34.2 (4.0)	0.14 (−0.07, 0.34)	0.03 (−0.02, 0.09)	1.5 (1.3, 1.9)	0.13 (0.11, 0.16)	0.98 (0.97, 0.99)
Upper Thigh Circumference (cm)	60.3 (5.0)	60.3 (4.9)	60.3 (4.9)	0.15 (−0.08, 0.38)	0.03 (−0.02, 0.08)	1.0 (0.8, 1.2)	0.12 (0.10, 0.15)	0.99 (0.98, 0.99)
Waist Circumference (umbilicus) (cm)	79.0 (9.8)	78.8 (9.5)	78.7 (9.5)	−0.07 (−0.51, 0.36)	−0.01 (−0.05, 0.04)	1.3 (1.1, 1.6)	0.11 (0.09, 0.14)	0.99 (0.98, 0.99)
Chest Circumference (cm)	93.2 (9.9)	92.6 (10.1)	93.0 (10.1)	−0.50 (−0.92, −0.07)	−0.05 (−0.09, −0.01)	1.2 (1.0, 1.5)	0.11 (0.09, 0.13)	0.99 (0.98, 0.99)
Waist Circumference (Low) (cm)	86.3 (7.5)	86.2 (7.6)	85.9 (7.3)	−0.03 (−0.29, 0.24)	0.00 (−0.04, 0.03)	0.8 (0.7, 1.0)	0.09 (0.07, 0.11)	0.99 (0.99, 1.00)
Torso Surface Area (cm^2)	6268 (1.12)	6282 (1.1)	6284 (1.2)	15 (−8, 38)	0.02 (−0.01, 0.05)	0.9 (0.8, 1.2)	0.08 (0.07, 0.10)	0.99 (0.99, 1.00)
Hip Circumference (cm)	99.9 (5.9)	99.9 (5.8)	99.7 (5.6)	0.07 (−0.11, 0.25)	0.01 (−0.02, 0.04)	0.5 (0.4, 0.6)	0.08 (0.06, 0.10)	0.99 (0.99, 1.00)
Total Body Surface Area (cm^3)	16308 (1635)	16384 (1610)	16354 (1606)	76 (31, 122)	0.05 (0.02, 0.08)	0.7 (0.6, 0.9)	0.07 (0.06, 0.09)	1.00 (0.99, 1.00)
High Hip Circumference (cm)	94.2 (6.2)	94.2 (6.1)	94.1 (5.9)	−0.01 (−0.17, 0.15)	0.00 (−0.03, 0.02)	0.4 (0.4, 0.5)	0.07 (0.05, 0.08)	1.00 (0.99, 1.00)
Waist Circumference (Narrowest) (cm)	74.1 (8.9)	74.2 (9.0)	74.0 (9.1)	0.09 (−0.09, 0.26)	0.01 (−0.01, 0.03)	0.6 (0.5, 0.8)	0.05 (0.04, 0.06)	1.00 (1.00, 1.00)
Total Body Volume (cm^3)	63494 (12104)	63729 (12050)	63617 (11989)	219 (48, 391)	0.02 (0.00, 0.04)	0.7 (0.6, 0.9)	0.04 (0.03, 0.05)	1.00 (1.00, 1.00)

Note; TE=Typical error.

	Session 1	Session 2						
Measurement	**Mean (SD)**	**Mean (SD)**	**Bias (95%CI)**	**Standardized Bias (95%CI)**	**TE (95%CI)**	**Percent TE (95%CI)**	**Standardized TE (95%CI)**	**ICC (95%CI)**
Calf Circumference (cm)	35.3 (2.3)	35.6 (2.2)	0.29 (0.13, 0.44)	0.06 (−0.06, 0.17)	0.39 (0.33, 0.48)	1.1 (0.9, 1.4)	0.29 (0.24, 0.36)	0.97 (0.95, 0.98)
Upper Bicep Circumference (cm)	28.8 (3.6)	28.7 (3.6)	−0.16 (−0.36, 0.05)	−0.04 (−0.10, 0.02)	0.51 (0.43, 0.63)	1.9 (1.6, 2.3)	0.15 (0.13, 0.19)	0.98 (0.96, 0.99)
Lower Bicep Circumference (cm)	26.3 (3.0)	26.2 (2.8)	−0.03 (−0.19, 0.14)	−0.01 (−0.06, 0.05)	0.42 (0.35, 0.52)	1.6 (1.3, 2.0)	0.15 (0.12, 0.18)	0.98 (0.97, 0.99)
Arm Surface Area (cm^2)	1254 (199)	1256 (197)	2.9 (−8.2, 12.0)	0.01 (−0.05, 0.07)	25.4 (21.3, 31.6)	2.2 (1.9, 2.8)	0.14 (0.12, 0.18)	0.98 (0.97, 0.99)
Arm Volume (cm^3)	2287 (666)	2271 (635)	−16 (−55, 24)	−0.02 (−0.07, 0.04)	100 (84, 124)	3.8 (3.1, 4.7)	0.13 (0.11, 0.16)	0.98 (0.97, 0.99)
Forearm Circumference (cm)	25.9 (2.8)	26.0 (2.8)	0.03 (0.10, 0.16)	0.01 (−0.04, 0.06)	0.33 (0.28, 0.41)	1.3 (1.1, 1.7)	0.12 (0.10, 0.16)	0.99 (0.97, 0.99)
Leg Surface Area (cm^2)	2255 (207)	2266 (206.3)	12 (3, 20)	0.06 (0.02, 0.10)	20.8 (17.4, 25.8)	0.9 (0.8, 1.2)	0.10 (0.09, 0.13)	0.99 (0.98, 0.99)
Lower Thigh Circumference (cm)	43.0 (3.0)	43.2 (3.0)	0.19 (0.07, 0.30)	0.06 (0.02, 0.10)	0.29 (0.25, 0.37)	0.7 (0.6, 0.8)	0.10 (0.08, 0.12)	0.99 (0.98, 0.99)
Neck Circumference (cm)	34.2 (3.9)	34.2 (3.9)	0.02 (−0.12, 0.16)	0.01 (−0.03, 0.04)	0.35 (0.29, 0.43)	1.1 (0.9, 1.3)	0.09 (0.08, 0.11)	0.99 (0.99, 1.00)
Mid-Thigh Circumference (cm)	56.4 (4.2)	56.5 (4.3)	0.12 (−0.02, 0.25)	0.03 (−0.01, 0.06)	0.34 (0.29, 0.42)	0.6 (0.5, 0.8)	0.08 (0.07, 0.10)	0.99 (0.99, 1.00)
Leg Volume (cm^3)	6235 (948)	6282 (956)	46 (17, 75)	0.05 (0.02, 0.08)	72.9 (61.0, 90.7)	1.1 (0.9, 1.4)	0.08 (0.06, 0.10)	0.99 (0.99, 1.00)
Chest Circumference (cm)	92.9 (9.9)	92.7 (9.9)	−0.23 (−0.50, 0.03)	0.07 (0.06, 0.09)	0.66 (0.55, 0.82)	0.7 (0.6, 0.9)	0.07 (0.06, 0.09)	1.00 (0.99, 1.00)
Upper Thigh Circumference (cm)	60.2 (5.0)	60.2 (4.9)	−0.01 (-0.14, 0.12)	0.00 (−0.03, 0.03)	0.33 (0.28, 0.41)	0.6 (0.5, 0.7)	0.07 (0.06, 0.09)	1.00 (0.99, 1.00)
Torso Surface Area (cm^2)	6332 (748)	6324 (739)	−8 (−24, 9)	−0.01 (−0.03, 0.01)	41.5 (34.7, 51.6)	0.7 (0.6, 0.8)	0.06 (0.05, 0.07)	1.00 (0.99, 1.00)
Waist Circumference (umbilicus) (cm)	78.9 (9.5)	78.9 (9.6)	0.00 (−0.21, 0.22)	0.00 (−0.02, 0.02)	0.53 (0.45, 0.66)	0.7 (0.5, 0.8)	0.06 (0.05, 0.07)	1.00 (0.99, 1.00)
Hip Circumference (cm)	99.9 (5.8)	100 (5.9)	0.08 (−0.03, 0.20)	0.01 (0.00, 0.03)	0.28 (0.23, 0.35)	0.3 (0.2 0.3)	0.05 (0.04, 0.06)	1.00 (1.00, 1.00)
Waist Circumference (Low) (cm)	86.2 (7.4)	86.2 (7.6)	0.00 (−0.12, 0.12)	0.00 (−0.02, 0.02)	0.31 (0.26, 0.39)	0.4 (0.3, 0.5)	0.05 (0.04, 0.06)	1.00 (1.00, 1.00)

Torso Volume (cm^3)	38973 (8773)	39039 (8736)	66 (−67, 198)	0.01 (0.01, 0.03)	333 (279, 415)	0.9 (0.8, 1.1)	0.05 (0.04, 0.06)	1.00 (1.00, 1.00)
Waist Circumference (Narrowest) (cm)	74.1 (9.0)	74.1 (9.1)	−0.02 (−0.15, 0.11)	0.00 (−0.02, 0.01)	0.32 (0.27, 0.40)	0.4 (0.4, 0.5)	0.04 (0.03, 0.05)	1.00 (1.00, 1.00)
Total Body Surface Area (cm^3)	16385 (1619)	16420 (1620)	33 (7, 60)	0.02 (0.00, 0.04)	65.3 (54.4, 81.6)	0.4 (0.3, 0.5)	0.04 (0.03, 0.05)	1.00 (1.00, 1.00)
High Hip Circumference (cm)	94.2 (6.1)	94.2 (6.1)	0.04 (−0.04, 0.12)	0.01 (−0.01, 0.02)	0.20 (0.17, 0.25)	0.2 (0.2, 0.3)	0.04 (0.03, 0.04)	1.00 (1.00, 1.00)
Total Body Volume (cm^3)	63613 (12042)	63796 (12064)	179 (63, 296)	0.02 (0.01, 0.03)	284 (236, 356)	0.4 (0.4, 0.5)	0.02 (0.02, 0.03)	1.00 (1.00, 1.00)

Note; TE=Typical error.

REFERENCES

Bigaard, J., Frederiksen, K., Tjønneland, A., Thomsen, B.L., Overvad, K., Heitmann, B.L., & Sørensen, T.I. (2005). Waist circumference and body composition in relation to all-cause mortality in middle-aged men and women. *International Journal of Obesity*, *29(7)*, 778–784.

Bragança, S., Arezes, P., Carvalho, M., & Ashdown, S.P. (2016). Current state of the art and enduring issues in anthropometric data collection. *DYNA*, *83(197)*, 22–30.

Brocherie, F., Girard, O., Forchino, F., Al Haddad, H., Dos Santos, G., & Millet, G. (2014). Relationships between anthropometric measures and athletic performance, with special reference to repeated-sprint ability, in the Qatar national soccer team. *Journal of Sports Sciences*, *32(13)*, 1243–1254.

Bullas, A.M., Choppin, S., Heller, B., & Wheat, J. (2016). Validity and repeatability of a depth camera-based surface imaging system for thigh volume measurement. *Journal of Sports Sciences*, *34(20)*, *1998–2004*.

Clarkson, S., Wheat, J., Heller, B., & Choppin, S. (2016). 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*, *34(11)*, 1006–1014.

Daanen, H.A.M., & Ter Haar, F.B. (2013). 3D whole body scanners revisited. Displays, 34, 270–275.

Hermassi, S., Schwesig, R., Wollny, R., Fieseler, G., van den Tillaar, R., Fernandez-Fernandez, J., Shephard, R.J., & Chelly, M.S. (2017). Shuttle versus straight repeated-sprint ability tests and their relationship to anthropometrics and explosive muscular performance in elite handball players. *Journal of Sports Medicine and Physical Fitness*, *58(11)*, 1625–1634.

Hopker, J., Coleman, D., Passfield, L., & Wiles, J. (2010). The effect of training volume and intensity on competitive cyclists' efficiency. *Applied Physiology, Nutrition, and Metabolism*, *35(1)*, 17–22.

Hopkins, W.G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30(1)*, 1–15.

Hopkins, W.G. (2007) A spreadsheet to compare means of two groups. *Sportscience*, 11, 22–23.

Hopkins, W.G. (2010). Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience*, *14*, 49–58.

Janssen, I., Katzmarzyk, P., & Ross, R. (2002). Body mass index, waist circumference, and health risk: Evidence in support of current National Institutes of Health guidelines. *Archives of Internal Medicine*, *162(18)*, 2074–2079.

Kordi, M., Haralabidis, N., Huby, M., Barratt, P.R., Howatson, G., & Wheat, J.S. (2018). Reliability and validity of depth camera 3D scanning to determine thigh volume. *Journal of Sports Sciences*, *37(1)*, 1–6.

Kuehnapfel, A., Ahnert, P., Loeffler, M., & Scholz, M. (2017). Body surface assessment with 3D laser-based anthropometry: reliability, validation, and improvement of empirical surface formulae. *European Journal of Applied Physiology*, *117(2)*, 371–380.

Lin, J.D., Chiou, W.K., Weng, H.F., Fang, J.T., & Liu, T.H. (2004). Application of three-dimensional body scanner: Observation of prevalence of metabolic syndrome. *Clinical Nutrition*, *23(6)*, 1313–1323.

Madden, A., & Smith, S. (2016). Body composition and morphological assessment of nutritional status in adults: A review of anthropometric variables. *Journal of Human Nutrition and Dietetics*, *29(1)*, 7–25.

Ng, B.K., Hinton, B.J., Fan, B., Kanaya, A.M., & Shepherd, J.A. (2016). Clinical anthropometrics and body composition from 3D whole-body surface scans. *European Journal of Clinical Nutrition*, *70(11)*, 1265–1270.

Ning, Y., Yang, S., Evans, R., Stern, K., Sun, M., Francis, S., & Wickham, G. (2014). Changes in body anthropometry and composition in obese adolescents in a lifestyle intervention program. *European Journal of Nutrition*, *53(4)*, 1093–1102.

Stewart, A., Marfell-Jones, M., Olds, T., & de Ridder, H. (2011). *International standards for anthropometric assessment*. Lower Hutt, NZ: International Society for the Advancement of Kinanthropometry.

Prokop, N., Reid, R., & Andersen, R. (2016). Seasonal changes in whole body and regional body composition profiles of elite collegiate ice-hockey players. *Journal of Strength and Conditioning Research*, *30(3)*, 684–692.

Rauter, S., Vodicar, J., & Simenko, J. (2017). Body asymmetries in young male road cyclists. *International Journal of Morphology*, *35(3)*, 907–912.

Raymond-Pope, C., Dengel, D., Fitzgerald, J., & Bosch, T. (2018). Association of compartmental leg lean mass measured by dual x-ray absorptiometry with force production. *Journal of Strength and Conditioning Research*. DOI: 10.1519/JSC.0000000000002688.

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.

Schranz, N., Tomkinson, G., Olds, T., & Daniell, N. (2010). Three-dimensional anthropometric analysis: Differences between elite Australian rowers and the general population. *Journal of Sports Sciences*, *28(5)*, 459–469.