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Is three-dimensional anthropometric analysis as good as traditional anthropometric analysis in predicting junior rowing performance?

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Abstract

With the use of three-dimensional whole body scanning technology, this study compared the 'traditional' anthropometric model [one-dimensional (1D) measurements] to a 'new' model [1D, two-dimensional (2D), and three-dimensional (3D) measurements] to determine: (1) which model predicted more of the variance in self-reported best 2000-m ergometry rowing performance; and (2) what were the best anthropometric predictors of ergometry performance, for junior rowers competing at the 2007 and 2008 Australian Rowing Championships. Each rower (257 females, 16.3 $\pm$ 1.4 years and 243 males, 16.6 $\pm$ 1.5 years) completed a performance and demographic questionnaire, had their mass, standing and sitting height physically measured and were landmarked and scanned using the *Vitus Smart*® 3D whole body scanner. Absolute and proportional anthropometric measurements were extracted from the scan files. Partial least squares regression analysis, with anthropometric measurements and age as predictor variables and self-reported best 2000-m ergometer time as the response variable, was used to first compare the two models and then to determine the best performance predictors. The variance explained by each model was similar for both male [76.1% (new) vs. 73.5% (traditional)] and female [72.3% (new) vs. 68.6% (traditional)] rowers. Overall, absolute rather than proportional measurements, and 2D and 3D rather than 1D measurements, were the best predictors of rowing ergometry performance, with whole body volume and surface area, standing height, mass and leg length the strongest individual predictors.

Keywords: *3D anthropometry, rowing, proportionality, dimensionality, adolescents*

Introduction

Rowing is one sport for which a number of studies have examined the anthropometric dimensions associated with success at the elite level, with most of the research focused on senior rowers. Several studies have examined the size differences between senior rowers and the general population across a number of one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) measurements (DeRose, Crawford, Kerr, Ward, & Ross, 1989; Kerr et al., 2007; Schranz, Tomkinson, Olds, & Daniell, 2010). The results of these studies demonstrate that lightweight rowers are typically similar in size, whereas heavyweight rowers are typically larger, with both lightweight and heavyweight rowers typically much less variable in size (DeRose et al., 1989; Kerr et al., 2007; Schranz et al., 2010). Comparisons between 'best' rowers (e.g. finalists) and 'rest' (e.g. non-finalists) have also been made (Kerr et al., 2007; Lawrence, 1984; Slater et al., 2005), with 'best' lightweight rowers typically exhibiting relatively smaller sum of skinfolds and larger arm girths and lengths, and 'best' heavyweight rowers exhibiting relatively smaller sum of skinfolds and percent body fat levels and larger mass, height and arm girths.

While fewer studies have been conducted on junior rowers, a systematic search of the peer-reviewed literature located five papers (and a total of three datasets) that examined either the anthropometric differences between 'best' and 'rest' junior rowers (Bourgois et al., 2000, 2001; Claessens et al., 2002, 2005) or correlated anthropometry with rowing performance (Russell, Rossignol, & Sparrow, 1998). Collectively, these studies show that 'best' junior male rowers are typically larger (taller, heavier and have larger girths, lengths and breadths) and leaner (smaller skinfolds) than the 'rest', yet are similarly

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sized when measurements were height-adjusted (Bourgois et al., 2000; Claessens et al., 2005; Russell et al., 1998). Likewise, 'best' junior female rowers typically exhibit larger length, girth, mass, standing height, and fat free mass measurements than the 'rest' (Bourgois et al., 2001; Claessens et al., 2002).

While these studies present the best available comparisons between successful and less successful elite junior rowers, only direct 1D anthropometric measurements (girths, lengths, breadths, skinfolds and estimated thigh cross-sectional areas) have previously been examined, and it is not known whether 2D and 3D measurements strengthen the performance prediction.

In the past, traditional anthropometric measurement techniques and equipment (e.g. girth tapes, stadiometers and skinfold calipers) have been employed for anthropometric surveys of athletes, allowing only for the capture of 1D measurements. Three-dimensional whole body scanning is a relatively new technology that captures a 3D surface image of a body from which numerous digital measurements can be extracted (e.g. girths, lengths, breadths, surface areas, cross-sectional areas and volumes) (Daniell, 2008). While 3D whole body scanners are expensive and require a high level of operator skill, they do offer several advantages over traditional anthropometry (Schranz et al., 2010). For example, 3D whole body scanners allow for the capture of surface anthropometric data in a more time-efficient and non-invasive manner, expanding the number of anthropometric dimensions that can be measured at any point in time, while also providing a historical record of the athlete that can be re-examined at any time without the athlete being present.

Therefore, a comparison of two different models for examining the dimensions of athletes can be made. Firstly, the 'traditional' model includes general measurements (direct measurements of mass, standing and sitting height, and two derived measurements in body mass index (BMI) and the sitting height-to-standing height ratio) along with 1D measurements (lengths, girths and breadths), which can all be captured using traditional measurement methods. Secondly, the 'new' model includes general measurements (still captured using traditional measurement methods), and 1D measurements as well as 2D and 3D measurements (volumes and cross-sectional and surface areas) all of which are captured using 3D whole body scanning technology.

Using 3D whole body scanning technology the aims of this study were: (1) to determine which model (the 'traditional' or the 'new') explains more of the variance in junior male and female rowing ergometry performance; and (2) which anthropometric measurements are the best predictors of junior male and female rowing ergometry performance. This study expands upon previous research into rowing and is the first 3D anthropometric study of competitive junior rowers.

Methods

Participants and sampling

Complete anthropometric and self-reported performance data were available on 500 junior rowers (257 females and 243 males aged less than 20 years) who competed at the 2007 and 2008 Australian Rowing Championships. This sample represented approximately 15% of all junior rowers who competed at the Championships in 2007 and 2008. Self-reported data on highest competitive level attained (prior to the Championships) were available for 370 rowers, with 78% (287 of 370) of rowers previously competing at club/school level, 13% (49 of 370) previously competing at the state level, 6% (22 of 370) previously medalling at the state level, 2% (8 of 370) previously competing at the national level, and 1% (4 of 370) previously medalling at the national level. The Human Research Ethics Committees of the Australian Institute of Sport and the University of South Australia granted ethics clearance for all testing procedures.

Landmarking and 3D scanning

The measurement procedures used in this study have been previously described in detail by Schranz et al. (2010), but are summarised below. Before being landmarked all rowers were required to fill out a demographic and performance questionnaire which also asked them to report their best 2000-m *Concept II*® ergometer performance. There was a correlation of $r = 0.73$ ($P < 0.0001$) and $r = 0.70$ ($P < 0.0001$) between self-reported best 2000-m time on the *Concept II*® ergometer and on-water performance (operationalised as single sculls race time at the Championships) for females ($n = 54$) and males ($n = 49$) respectively. However, because race time at the Championships was available for only a small subset of competitors ($n = 61$ and $n = 55$ for females and males respectively), self-reported 2000-m ergometer time was used as the performance variable.

Once ushered inside their landmarking booth, rowers were asked to change into form-fitting underwear (or their rowing suit) and then had their mass, standing and sitting height physically measured in duplicate, using protocols specified by the International Society for the Advancement for Kinanthropometry (ISAK) (Marfell-Jones, Olds, Stewart, & Carter, 2006). Anthropometrists accredited at Level 2 (or higher) by ISAK took all survey measurements. All anthropometrists involved in surveying were trained in the landmarking protocols (Olds et al.,

2004) by ISAK accredited Level 3 and 4 anthropometrists. The reliability and validity of each anthropometrist was checked during training against a Level 3 or a Level 4 anthropometrist, with percent technical errors less than 1% for all physical measurements.

All rowers were shown the standard scanning pose before 23 surface landmarks were located via palpation of the body's surface and marked with raised markers (Schranz et al., 2010). All landmarks were located on the right side of the body with the exception of the acromion (scapula) and iliac crest (hip) landmarks, which were placed on both the right and left sides of the body. Rowers were then asked to put on a swimming cap before being ushered into the *Vitus Smart*® 3D whole body scanner (*Human Solutions,* Kaiserslautern, Germany) at which time they were positioned in the standard scanning pose before being scanned. The total burden time per rower was 15 minutes.

File conversion and measurement extraction

Following conversion of all scan files, *Digisize v2.3* (*Cyberware,* Monterey, CA, USA) and *CySlice v3.4* (*Headus,* Perth, WA) software was used to extract 36 length, breadth, girth, cross-sectional and surface area, and volume measurements. This digital process took a total of 30 minutes per scan and was completed post-survey. Digital 3D measurements demonstrate good test-retest reliability, with trivial systematic errors [median effect size $\pm$ 95% confidence interval: 0.00 $\pm$ 0.03], small random errors [percent technical error: 0.69 $\pm$ 0.35%] and very high test-retest correlations [intra-class correlation coefficient: 0.997 $\pm$ 0.012] (Schranz et al., 2010).

Data checking and cleaning

Once all measurements were extracted from each 3D scan file, all absolute anthropometric data (with the exception of mass, standing height and whole body surface area and volume) were normalised using geometric scaling to eliminate the effect of overall body size (resulting in 39 proportional measurements that were included along with 39 absolute measurements). Girths, lengths and breadths were expressed as a fraction of standing height, surface areas and cross-sectional areas as a fraction of total body surface area, and segmental volumes as a fraction of whole-body volume (Olds, Norton, Van Ly, & Lowe, 1995). Data cleaning and checking procedures were then conducted to ensure quality of the data.

Statistical analysis

Because there are anthropometric and performance differences between junior male and female rowers, all statistical analyses were stratified by gender to avoid any gender effect. The predictor variables were age plus all anthropometric measurements [$n = 79$ predictors, with 44% (35 of 79) 1D measurements, 48% (38 of 79) 2D and 3D measurements, and 6% (5 of 79) general measurements (i.e. direct measurements of mass, standing and sitting height, and two derived measurements in BMI and the sitting height-to-standing height ratio)] and the response variable was self-reported best 2000-m *Concept II*® rowing ergometer time.

Partial Least Squares regression was used to determine which model (the 'traditional' or the 'new') explained more variance in rowing performance. The traditional model, which used age, 1D and general measurements as the predictor variables (n = 41 predictors) was analysed first. The new model, which used age, 1D, 2D, 3D and general measurements as the predictor variables (n = 79 predictors) was analysed second. [See Appendix 1 for a list of all measurements (predictor variables) included in each model].

The new model was used to determine which anthropometric characteristics were the best predictors of rowing ergometry performance.

Partial Least Squares is a predictive method that works by reducing both the predictor (x) and response (y) variables to principal components (Bastien, Vinzi, & Tenenhaus, 2005). The x-components are then used to predict the y-component scores, with the predicted y-component scores used to predict the raw y-variable(s). When deriving the x-components, which are a linear combination of the x-variables, the Partial Least Squares algorithm iteratively maximises the explanation of the covariance between the x-components and the raw y-variable(s). The optimal (and most parsimonious) model was determined by leave-one-out cross-validation, with 0.05 adopted as the criterion for significance. The Variable Importance in Projection statistic quantified the relative importance of each x-variable for each x-component. Variables with Variable Importance in Projection s $>$ 0.8 are considered to contribute significantly to the model and have a high predictive power (Wold, 1995). The advantages of Partial Least Squares are that while the x-variables may be collinear, the x-components will be independent, and while there may be missing data for some of the x-variables, a score will be computed for every missing case.

Results

Table I shows the descriptive statistics for the junior male and female rowers separately.

Male rowers

Three components were extracted when the traditional Partial Least Squares regression model was

Table I. Descriptive statistics for the sample of junior rowers who competed at the 2007 and 2008 Australian Rowing Championships and for whom there is complete anthropometric and performance data.

	Females (n = 257)		Males (n = 243)	
	mean	s	mean	s
Age (years)	16.3	1.4	16.6	1.5
Mass (kg)	65.2	8.7	76.3	11.0
Standing Height (cm)	171.2	6.6	182.8	7.8
Self- reported best 2000-m Concept II time (s)	475.1	44.2	413.4	34.4

Note: The correlation between self-reported best 2000-m time on the *Concept II*® ergometer and on-water performance (operationalised as single sculls race time at the Championships) was $r = 0.73$ ($P < 0.0001$) for females ($n = 54$) and $r = 0.70$ ($P < 0.0001$) for males ($n = 49$).

analysed for junior male rowers, which when combined explained 73.5% of the variance in rowing ergometry performance (taken separately they explained 56.9%, 13.7% and 2.9%). In contrast, four components were extracted when the new Partial Least Squares regression model was analysed, which when combined explained 76.1% of the variance (taken separately they explained 53.7%, 16.1%, 3.4% and 2.9%).

Examination of the new Partial Least Squares regression model shows that the five most important predictors of rowing ergometry performance for junior male rowers were whole body volume, whole body surface area, standing height, leg length and mass (Figure 1). Of those variables with significant Variable Importance in Projections (i.e. Variable Importance in Projections > 0.8), 80% (24 of 30) were absolute measurements and 60% (18 of 30) were 2D and 3D measurements (as compared to 48% of all inputs in the new model that were 2D and 3D measurements).

Female rowers

Four components were extracted when the traditional Partial Least Squares regression model was analysed for junior female rowers, which when combined explained 68.6% of the variance in rowing ergometry performance (taken separately they explain 45.2%, 10.6%, 8.2% and 4.6%). Similarly, four components were extracted when the new Partial Least Squares regression model was analysed, which when combined explained 72.3% of the variance (taken separately they explain 42.6%, 15.4%, 10.7% and 3.6%).

Further examination of the new Partial Least Squares regression model shows that the five most important predictors of rowing ergometry performance for junior female rowers were whole body volume, whole body surface area, mass, standing height and leg length (see Figure 1). Of those measurements with significant Variable Importance in Projections, 72% (18 of 25) were absolute measurements and 56% (14 of 25) were 2D and 3D measurements.

Differences between male and female predictors

A comparison of the two new Partial Least Squares regression models show that the same predictors were typically significant for both males and females. For example, 93% (23 of 25) of the significant predictors observed for females were also significant for males (Figure 1), with the remaining 7% (2 of 25) falling just below the 0.8 threshold for significance. In addition, 77% (23 of 30) of the significant predictors observed for males were also significant for females, with several of the remaining predictors (forearm volume, forearm surface area, and sitting height) demonstrating noticeably different Variable Importance in Projections between the sexes (Figure 1).

Discussion

Explanation of main findings

The main findings from this study for rowing ergometry performance were that: (a) traditional and new models explain similar amounts of variance; (b) absolute measurements were generally more important than proportional measurements; and (c) 2D and 3D measurements were generally more important than 1D measurements.

Despite the fact that the traditional and new predictive models explain similar amounts of variance in rowing ergometry performance, 3D whole body scanning boasts a range of benefits over and above that of traditional measurement techniques albeit excluding skinfold measures that are known to be good predictors of rowing performance (Bourgois et al., 2000, 2001; Claessens et al., 2002, 2005). Firstly, 3D scanning considerably expands the repertory of traditional anthropometry by allowing 2D and 3D measurements of volumes, cross-sectional and surface areas and shape contours. Secondly, it allows 1D, 2D and 3D measurements to be captured in a more time-efficient and non-invasive manner, which reduces participant burden. Thirdly, it provides a historical record of each athlete at a particular point in time, which can be re-examined in the future without the athlete present

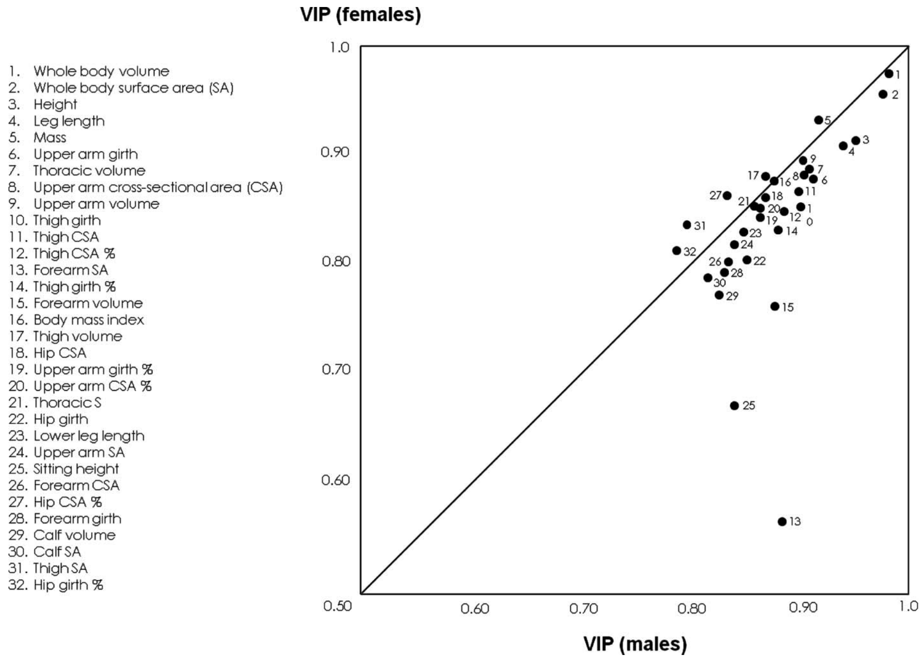

Figure 1. Variable Importance in Projection (VIP) for junior male and female rowers. Only those variables with VIPs greater than 0.8 are shown. The diagonal line represents the 'identity' line and therefore any variable which falls on this line has a similar VIP for both males and females. Note, % = proportional measurement, CSA = cross-sectional area, SA = surface area.

and from which additional anthropometric measurements can be retrospectively derived.

The higher predictive importance of absolute measurements could be because junior rowers display a wide range of body sizes and are at different stages of maturation. While overall body size (as indicated by whole body surface area and volume) is the most important dimension, the relative importance of regional body size (e.g. thorax, arms, legs) warrants exploration. Further analysis of the current dataset reveals that for female junior rowers, leg size is relatively more important than arm, chest and hip size, with 33% (6 of 18) of the significant absolute measurements being leg measurements. On the other hand, arm measurements, which comprise 33% (8 of 24) of the significant absolute measurements, are relatively more important for male junior rowers than measurements of the leg, chest and hip. These findings highlight that future anthropometric surveys should include both global and regional measures of body size.

While 2D and 3D measurements were generally more important than the range of 1D measurements taken here, whole body surface area and volume were shown to be the strongest predictors of rowing ergometry performance for both male and female junior rowers. Whole body 3D measures while easily captured from a 3D scanner, are often estimated from simple prediction equations that use directly measured standing height and mass values as inputs (Tikuisis, Meunier, & Jubenville, 2001). To examine the difference in the relative importance of measured and predicted whole body 3D measures, we re-ran the new regression model and included both measured and predicted whole body surface area values, the latter of which were generated using the Tikuisis et al. (2001) prediction equation. The results of this secondary analysis showed that predicted whole body surface area was ranked in the top five most important predictors of rowing ergometry performance for both male and female junior rowers, along with measured whole body surface area and volume (the top two ranked variables for both genders), mass and standing height. Therefore, while 3D scanning provides a number of benefits to athlete surveying, the results of this secondary analysis show that predicted whole body 3D measures (such as whole body surface area) can be confidently used as surrogates for direct whole body 3D measures.

Nonetheless, future anthropometric rowing surveys may wish to consider incorporating 3D anthropometry, given that 2D and 3D measurements were generally more important predictors of rowing ergometry performance in juniors than the range of 1D measurements taken here. Future rowing surveys that use 3D scanning could take the examination of anthropometric measurements and performance further by capturing body shape variants using cluster analysis. While longitudinal studies incorporating 3D analysis could also add to previous research by: (a) looking at how sensitive anthropometric changes within and between seasons are at determining changes in performance; and (b) whether the anthropometric measurements of a junior rower relate well to their anthropometry and rowing performance as a senior.

Comparisons with other studies

Previous studies have commonly reported mass and standing height as important predictors of rowing performance in juniors (Bourgois et al., 2000, 2001; Claessens et al., 2002, 2005; Russell et al., 1998) and in senior heavyweight rowers (Kerr et al., 2007; Schranz et al., 2010), with standing height, not mass (due to the mass restriction for eligibility), important in senior lightweight rowers (Slater et al., 2005). In addition to these traditional measures, a study by Schranz (2008) found that in senior rowers, 3D whole body and segmental surface areas and volumes were the best predictors of rowing ergometry performance, with arm (males and females), thoracic (males), and thigh (females) volumes and surface areas the next most important predictors.

In support of previous findings, this study also found mass and standing height to be significant and highly ranked predictors for both genders, as well as several 3D measures that are strongly correlated with mass and standing height (e.g. whole body surface area and whole body volume). Previous studies have generally reported that the next most important predictors of junior rowing performance (exclusive of mass, standing and sitting height) are measurements of arm and leg size, and body fat (Bourgois et al., 2000, 2001; Claessens et al., 2002, 2005). Similar, results have also been found for senior heavyweight rowers, with upper arm and thigh size generally more important than forearm and calf size (Schranz et al., 2010). This study provides support for these findings as measurements of arm and thigh size were significant and highly ranked predictors of junior rowing ergometry performance.

Strengths and limitations

In this study, rowers participating at the 2007 and 2008 Australian Rowing Championships were recruited by convenience. Although this sample represented approximately 15% of all junior rowers competing at the Championships in both years, it is possible that the convenience sampling resulted in an under-representation of rowers in some events, an over-representation of rowers in others, and a sample not representative in terms of physical performance, skill level, or experience. Skinfold measurements were not collected in this study and because previous studies (Bourgois et al., 2000; Claessens et al., 2005; Kerr et al., 2007) have shown that successful rowers (both juniors and seniors) tend to have smaller skinfolds than less successful rowers, the inclusion of skinfolds would have allowed for a more comprehensive analysis.

Rowing performance was operationalised as self-reported best 2000-m performance time on a *Concept II*® rowing ergometer. *Concept II*® rowing ergometer performance has been previously reported to be both a reliable (95% limits of agreement < 2.7%) (Macfarlane, Edmond, & Walmsley, 1997) and valid (95% limits of agreement < 1.9%) (Schabort, Hawley, Hopkins, & Blum, 1999; Soper & Hume, 2004) measure of on-water rowing performance. It is also important to remember that the best *Concept II*® rowing ergometer performances of the rowers may not have coincided in time with the anthropometric measurements, or the measures of on-water performance, that were taken in this study. It is possible that 'best' rowing ergometry performances were achieved weeks, months or even years beforehand.

It is also acknowledged that the variability in biological age of rowers included in this study is quite large (Table I). Therefore, the variability in maturation amongst the rowers (especially the males) could be substantial and could impact rowing ergometry performance. To control for the effect of age on rowing ergometry performance, age was included as a predictor variable in all of our Partial Least Squares regressions. In both the traditional and new models, and for both males and females, age was not considered to be significantly important (Variable Importance in Projection < 0.8). However, it is important to consider the relationship between age and body size (i.e. body size increases with age throughout adolescence), a relationship that was moderately strong ($r = 0.33$) in this dataset. Therefore, while age was not a significantly important predictor, other measurements (e.g. whole body surface area and volume, standing height and mass), which were the strongest predictors of rowing ergometry performance, probably reflect the importance of biological maturation.

There were also a number of strengths to this study. This study captured and analysed anthropometric data for a large sample of elite junior rowers. A large range of anthropometric measurements not previously published in the scientific literature, at least not for junior rowers, were captured and analysed in this study, including volume and surface and cross-sectional area measurements. The burden per rower was much less than in previous studies as our procedures required each rower to only be present for 15 minutes (as 30 minutes worth of digital analysis was completed post-survey without the rowers present), allowing for a much quicker participant throughput.

Conclusions

Three-dimensional whole body scanning provides a new model for analysing the anthropometry of athletes. While both the 'traditional' and 'new' models explain similar amounts of variance in rowing performance, three-dimensional whole body scanning allows for the capture of more anthropometric measurements in a more time efficient manner, as well as a number of other technological benefits. This study has shown that successful competitive junior rowers do possess distinct morphological characteristics and 3D measurements such as whole body volumes and surface areas, which were not identified in previous studies, can complement traditional 1D measurements. With this new understanding of what a successful elite junior rower looks like, future anthropometric rowing surveys may wish to consider incorporating 3D anthropometry (or the use of predictive equations for estimation of whole body 3D measures) into their battery of tests to complement previous work that has employed traditional measurement techniques.

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Appendix 1. Measurements included in each analysis model.

Type — model/s included in (% contribution to new model)	Measurement
Other — traditional & new model (1.3%)	• Age
General — traditional and new model (6.3%)	BODY SIZE MEASURES • Mass[a] • Standing height[a] • Sitting height[a] DERIVED MEASURES • BMI [p] • Sitting height-to-Standing height[p]
One-dimensional — traditional and new model (44.3%)	GIRTHS • Upper arm[ap] • Forearm[ap] • Hip[ap] • Waist[ap] • Mid thigh[ap] • Calf[ap] BREADTHS • Bigonial[ap] • Biacromial[ap] • Elbow[ap] • Biiliocristal[ap] • Knee[ap] LENGTHS • Upper arm[ap] • Forearm[ap] • Upper leg[ap] • Lower leg[ap] • Leg[ap] DERIVED MEASURES • Biacromial-to-Biiliocristal ratio[p] • Brachial index[p] • Crural index[p]
Two-dimensional — new model (15.2%)	CROSS-SECTONAL AREAS • Upper arm[ap] • Forearm[ap] • Waist[ap] • Hip[ap] • Mid thigh[ap] • Calf[ap]
Three-dimensional — new model (32.9%)	SURFACE AREAS • Whole body[a] • Upper arm[ap] • Forearm[ap] • Thoracic[ap] • Gluteal[ap] • Thigh[ap] • Calf[ap] VOLUMES • Whole body[a] • Upper arm[ap] • Forearm[ap] • Thoracic[ap] • Gluteal[ap] • Thigh[ap] • Calf[ap]

Note:[a] = absolute measurement,[p] = proportional measurement, BMI = body mass index.