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Technical Note: Standardized Anthropological Measurement of Postcranial Bones Using Three-Dimensional Models in CAD Software

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Highlights

- Standardized virtual protocols to conduct linear skeletal measurements are needed
- A standardized virtual protocol for linear skeletal measurements is introduced
- Semi-automated anthropometric measurements using CAD software have high reliability
- 3D virtual protocols have broad application to forensic anthropology

Abstract

This study introduces a standardized protocol for conducting linear measurements of postcranial skeletal elements using three-dimensional (3D) models constructed from post-mortem computed tomography (PMCT) scans. Using femoral DICOM datasets, reference planes were generated and plane-to-plane measurements were conducted on 3D surface rendered models. Bicondylar length, epicondylar breadth, anterior-posterior (AP) diameter, medial-lateral (ML) diameter and cortical area at the midshaft were measured by four observers to test the measurement error variance and observer agreement of the protocol (n=6). Intra-observer error resulted in a mean relative technical error of measurement (%TEM) of 0.11 and an intraclass correlation coefficient (ICC) of 0.999 (CI=0.998-1.000); inter-observer error resulted in a mean %TEM of 0.54 and ICC of 0.996 (CI=0.979-1.000) for bicondylar length. Epicondylar breadth, AP diameter, ML diameter and cortical area also yielded minimal error. Precision testing demonstrated that the approach is highly repeatable and is recommended for implementation in anthropological investigation and research. This study exploits the benefits of virtual anthropology, introducing an innovative, standardized alternative to dry bone osteometric measurements.

Keywords: forensic anthropology; multi-slice computed tomography; reverse engineering; technical error of measurement; precision; observer-agreement

Introduction

The measurement and examination of human dry bones is an established anthropological technique in the identification of unknown human remains. However, maceration prior to examination can be a time-consuming, resource intensive process and may be prohibited by national regulations or religious practices. As a non-invasive alternative, the use of radiology is emerging as a reliable tool for rapid post-mortem skeletal assessment. As stated in the INTERPOL DVI Guide [1], multi-slice computed tomography (MSCT) is a valuable tool in the post-mortem identification process and is now conducted systematically during mass disasters. The application of post-mortem computed tomography (PMCT) played an important role in Disaster Victim Identification in Australia during the 2009 Victorian Bushfires Disaster [2, 3] and PMCT scanners are gaining popularity in medical examiner office settings [4, 5], constituting standard protocol for post-mortem examination in Australia, Europe and worldwide.

Two-dimensional (2D) MSCT scout views, which are equivalent to plain film and digital x-ray techniques, have been previously used to conduct virtual linear measurements such as in leg length discrepancy [6-9], however depending on the orientation of the bone in the image, anatomical landmarks can be difficult to identify. Additionally, distortion of the image and superimposition of structures can also make identifying landmarks problematic. From a forensic anthropological perspective, Brough et al. [10], Robinson et al. [11] and Lottering et al. [12] have all introduced standardized protocols for conducting measurements of the juvenile clavicle, lower limb bones and the juvenile skull using MSCT, respectively, and report comparable accuracies between MSCT-derived measurements and traditional osteometric measurements. The use of reverse engineering computer software using three-dimensional surface rendered models for measuring other postcranial bones has not been investigated, and a standardized protocol has not been introduced. Considering anthropological examination routinely utilizes postcranial bones in DVI and medico-legal investigation, it is essential to have standard procedures in place for measurement of all bones, enabling identifiable information to be estimated that genetic analysis cannot provide.

Computed assisted design (CAD) software such as Geomagic Design X™ (3D Systems, Inc., United States), allows the user to generate three-dimensional (3D) virtual models of skeletal elements, enabling complete visualisation of all surface bony features. The 3D surface rendered bones are visualised in x, y and z planes, therefore the model can be rotated to define specific anatomical landmarks, allowing accurate metric dimensions to be obtained through the application of semi-automated reference planes. CAD software also allows for analyses to be conducted from remote locations immediately, or at a later date, and offers a method of virtual recordkeeping of the reference geometries and bone model. In concordance with a 2009 U.S. National Research Council and U.S. National Academy of Sciences (NAS) report [13], it is critical that scientific methods be validated and standardized. The current study introduces technologically enhanced standardized protocols for performing linear measurements of postcranial bones, and assesses the precision and observer agreement using three-dimensional models of the human femur. This method aims to demonstrate the benefits of ‘virtual forensic anthropology’ as a non-invasive approach to obtain reproducible osteometric measurements from post-mortem and/or clinical imaging acquired data, to advance medico-legal death investigations.

Materials and Methods

A subset of six post-mortem computed tomography (PMCT) scans of the femoral region were accessed from the Skeletal Biology and Forensic Anthropology Virtual Osteological Database, housed at the Queensland University of Technology for precision testing [12, 14, 15]. Specifically, the post-mortem DICOM (Digital Imaging and Communications in Medicine) datasets utilized in this study were acquired from Queensland

Health Forensic and Scientific Services (QHFSS) – Forensic Pathology Mortuary using a Toshiba® Aquilion LB™ 16-slice CT scanner (Toshiba Medical Systems, Tochigi, Japan) (slice thickness: 2mm, overlap: 1.6mm, voxel dimensions: 0.78mm x 0.78mm x 2.0mm) between 2011 and 2014. Ethics was approved by the QHFSS Human Research Ethics Committee with Genuine Researcher Approval from the State Coroner and QUT Ratification (Ethics #: 1300000091).

Bone Measurements

Threshold-based segmentation (>300HU) of the femora was performed using Amira® (VSG, FEI Company, United States) to produce a three-dimensional (3D) surface reconstruction from the thin-slice stacked DICOM data. A single HU threshold cannot be used for all individuals since the density of the tissues slightly changes between each subject. As a result, a slight change in HU will produce a slightly different surface. Additionally, Amira® and other 3D treatment software programs should be used with caution, as potential under or overestimation in the morphology of the volumes reconstructed may slightly influence the consequent measurements.

The 3D bone model generated was imported into Geomagic Design X™ (3D Systems, Inc., United States) for virtual osteometric examination. A series of anatomical reference planes were constructed to represent a 'virtual osteometric board', allowing automated placement of extreme position planes to quantify bicondylar length of the femur (Fig 1). Geomagic Design X™ is an appropriate modelling tool for conducting standardized linear measurements as the extreme position plane is an inbuilt function which automatically generates the most proximal/distal or medial/lateral plane based on the normal vector of a nominated plane. Alternative software may be less expensive and more accessible to students for some of the steps in this protocol e.g. Meshmixer and IhpFusionBox.

Additional anthropometric measures of the femur were taken to demonstrate the wide application of the protocol, including epicondylar breadth, cortical diameters of the midshaft and cortical area of the midshaft (Fig. 2). Refer to supplementary material for further detail of the methodological protocol to quantify femoral proportions using Geomagic Design X^{TM}.

Manually drawing reference planes to generate extreme position planes can be used quickly to conduct any linear measurements of a bone, for example, maximum length of the clavicle; maximum diaphyseal length of the subadult tibia; maximum length and epicondylar breadth of the humerus; and height and breadth of the scapula as demonstrated in Fig. 3, however it is essential that the skeletal element is first aligned in the correct anatomical position by the user. This technique is simple and extremely fast to perform. Point to point measurements can also be conducted when required i.e. diameter of the head of the humerus in Fig. 3C.

Observer Error

Following automated threshold-based segmentation, bicondylar femoral length, femoral epicondylar breadth, AP diameter, ML diameter and cortical area at the femoral midshaft were measured three times (on three separate days with a minimum of 24 hours between) on six of the femoral 3D reconstructions (n=6) by four independent observers to assess inter-observer and intra-observer error. The observers exhibited varying degrees of experience in anatomical imaging interpretation and use of reverse engineering software. In addition, bicondylar length and epicondylar breadth were measured three times on six dry femora by the same observers using a physical osteometric board to assess intra- and inter-observer error using the traditional physical method. Observer error was assessed with technical error of measurement (TEM) and relative technical error of measurement (%TEM) following the protocol described by Stull et al. [16]. Observer agreement was also assessed using the intra-class correlation coefficient (ICC) function in SPSS, version 22 (2013; IBM Corporation, Armonk, NY). Intra-observer error was calculated using a two-way mixed effects single measures model ICC with absolute agreement, while inter-observer error was calculated using a two-way random effects average measures model ICC with absolute agreement. The ICC is employed when assessing consistency in measurement across multiple groups, in this case, multiple evaluation days (intra-observer testing) or multiple observers (inter-observer testing). Estimates between 0.75 and 1.0 indicate excellent observer agreement [17].

Results

Table 1 provides intra-observer *(MR)* TEM, %TEM and ICC for femoral bicondylar length, epicondylar breadth, AP diameter, ML diameter and cortical area for the six samples measured over three days. Of these measurements, TEM did not exceed 0.53mm (for the linear measurements; TEM=8.37mm^2 for cortical area). The highest %TEM was observed in the measurement of ML diameter (1.50%) and the lowest %TEM was 0.11% for bicondylar length. Table 2 provides inter-observer TEM, %TEM and ICC for femoral bicondylar length, epicondylar breadth, AP diameter, ML diameter and cortical area for the six samples for all observers on three evaluation days. Overall, of these measurements, the highest TEM was 2.58mm for bicondylar length (excluding cortical area which was 13.91mm^2). The highest %TEM of all measurements was 2.72% for AP diameter and the lowest %TEM was 0.23% for epicondylar breadth. Despite varying levels of anatomical and software expertise, retest correlations demonstrate that all observers were in “excellent agreement” with ICC values >0.75.

Table 3 provides inter-observer error TEM, %TEM and ICC for femoral bicondylar length and epicondylar breadth measured on separate dry samples using a traditional osteometric board. Intra-observer and inter-observer error for dry femoral measurements were minimal. Dry bicondylar length measurements resulted in an intra-observer TEM of 0.95mm, %TEM of 0.22% and ICC of 0.999 (CI=0.994-1.000), while inter-observer error resulted in a mean TEM of 0.97mm, %TEM of 0.24% and ICC of 0.996 (CI=0.958-1.000). For epicondylar breadth, intra-observer error resulted in a TEM of 0.24mm, %TEM of 0.32% and ICC of 0.998 (CI=0.991-1.000), while inter-observer error resulted in a mean TEM of 0.54mm, %TEM of 0.73% and ICC of 0.997 (CI=0.986-1.000).

Discussion

Anthropological examination using 3D computed tomography modeling is a non-invasive alternative to traditional time-consuming maceration procedures of decomposed or fleshed remains, and accurately replicates traditional measurement techniques of dry bones. In addition, virtual forensic anthropology enables analyses to be conducted from remote locations almost immediately and is therefore regarded as a valuable tool in disaster victim identification, drastically reducing examination time and allowing the data to be stored as a virtual reference collection.

As an extension of the protocol published by Lottering et al. [12], this paper introduces a robust semi-automated osteometric measurement protocol for obtaining linear metric information of postcranial bones using reverse engineering CAD software. MSCT protocols have been used to measure lower limb bones [11] and the clavicle [10], utilizing multi-planar reformatted (MPR) models to delineate boundaries at the most extreme points visible on the bone by using contiguous orthoslices. Utilizing an orthogonal plane MPR technique, three perpendicular, arbitrary planes are displayed simultaneously, with graphical cues indicating their relative orientations and intersections; the planes can be moved within the 3D image volume to provide a cross-sectional view at any desired location along the adjusted principal axes, for the identification of anatomical landmarks. Examination of such orthoslices however, requires anatomical imaging knowledge as investigators are required to mentally transform multiple 2D images to form a 3D representation of the anatomy and pathology. Virtual linear measurements have also been conducted on 3D models of the os coxae using an osteometric toolkit in Mimics® (Materialise, Leuven, Belgium) [18]. However, this method relies on the user to manually select a landmark, with the software calculating the linear distance between the user-defined points. A benefit of CAD applications such as those used in this study, is that planes are able to be automatically aligned to the most extreme points of the bone quickly and with ease, reducing observer bias that may present in manual selection of landmarks.

Numerous validation studies demonstrate negligible differences in osteometric measurements between physical dry skeletal samples and MSCT scans of the same samples [10-12, 16, 19, 20], including a study from our own laboratory that compared cranial length and breadth using callipers on three dry skulls to virtual measurement from the MSCT scan data [12]. This study demonstrated negligible error with a TEM of <0.19mm (R=0.999) [12], suggesting that CT-derived measurements can be accurately employed in dry bone-derived formulae associated with the establishment of a biological profile, further professing the congruity of innovative imaging approaches in modern anthropology. When the same observers in this study measured six dry, intact femora over three days using an osteometric board, intra- and inter-observer testing exhibited comparable results to the semi-automated, virtual protocol introduced in this study (dry femora inter-observer %TEM: 0.30%; virtual femora inter-observer %TEM: 0.51% for bicondylar length), advocating the precision and repeatability of the approach. "Excellent Agreement" (ICC > 0.750) [21] for retest correlation between the four observers in this study indicates that individuals with variable experience in anatomical science and reverse engineering software are able to reliably apply the technique. Despite the measurement of the bicondylar femoral length relying on observer judgement due to the scan resolution, where anatomical experience is important in selecting the proximal plane by visually separating the head of the femur from the acetabulum, observer agreement was high, validating the robustness of the protocol. Although manually segmenting the head of the femur from the acetabulum in Amira® was an option, the authors determined that the view-clip tool in Geomagic Design X™ was a significantly faster method for establishing the most proximal point of the femur.

This study highlights the advantages of CAD software in osteometric evaluation, including i) observing hidden/internal bony features; ii) using extreme position planes to accelerate the measurement process; iii) reducing the subjective error associated with manual identification of landmarks; iv) allowing virtual recordkeeping of the geometries and bone model; and v) to offer a high level of measurement accuracy. To capitalize on the 3D capabilities of PMCT data, our protocol involved threshold-based segmentation to generate a

3D surface reconstruction or isosurface, which serves as an approximate virtual representation of the geometry of the bone. High-quality 3D models allow a detailed visualization of the bone surface and morphological features [22]. Furthermore, it has been shown that errors associated with virtual bone models are typically no larger than the scan resolution [23]. These models also allow the viewer to observe 'hidden features' such as the medullary cavities of long bones and the cranial sinuses which are not visible from the surface [24], and perform advanced osteometry on complex 3D bone morphologies providing opportunities for novel geometric morphometric techniques to be developed in addition to traditional measurements. Utilizing reverse engineering capabilities in CAD programs, which exhibit multi-axis modalities, automated plane-to-plane measurements are derived with reference to the local geometry of the surface i.e. extreme positions. The measurement protocols introduced in this paper utilize silhouette curves, which identify the outermost boundary of the bone, however extreme position planes can also be fitted directly to the isosurface mesh of any bone, which can accelerate the measurement process. The use of extreme position planes in this study ultimately reduced the subjective error associated with manual identification of landmarks. Being a computer-based technology, CAD software offers the distinct advantage of saving all created reference geometries and curves along with a copy of the bone model for the purpose of recordkeeping and/or to serve as a basis for obtaining additional measurements in the future. Reverse engineering platforms also provide submillimetre measurements offering a high level of measurement accuracy, which is otherwise unobtainable with standard anthropometric callipers and osteometric boards. However, it needs to be noted that the measurements are limited by the resolution of the scan. A reverse engineering approach allows a more detailed metric analysis, which is beneficial for small bony structures i.e. neonate or fragmentary remains, and is particularly important for the design of orthopaedic implants for surgical planning.

To highlight the wide application of this virtual protocol, a number of postcranial skeletal elements were measured in this study as per the standard anthropological measurements defined in Buikstra and Ubelaker [25] (Fig. 3). As evident in Fig. 3, which utilized cranial/cervical spine clinical datasets from the Skeletal Biology and Forensic Anthropology Virtual Osteological Database [12], scan parameters with slice thicknesses under 1mm (voxel dimensions: 0.391 x 0.391 x 0.30mm) are optimal for visualizing finer anatomical detail and reducing partial volume effects. Furthermore, the protocol introduced in this manuscript refers to the mathematical technique associated with the construction of a reference plane network and can therefore be adapted for use in other engineering softwares, or expansions to open source projects could be developed to model the novel methodology.

Although this protocol was specifically developed for conducting osteometric analysis for forensic anthropological research and investigation purposes, the method can also be applied in clinical settings for assessing growth rates, anatomical variation, surgical planning and designing prosthetic and orthopaedic implants. For example, digital preoperative planning is frequently conducted in primary total hip arthroplasty with success [26], however the process may benefit from the application of 3D software for a more complex and accurate preoperative analysis for personalized patient care.

This paper introduces a protocol for conducting linear measurements on postcranial 3D surface rendered bone models from PMCT scans of Australian individuals. The precision testing results demonstrate that the technique is highly repeatable between observers of varying software capabilities and anatomical knowledge, indicating that this standardized protocol is applicable for use in post-mortem anthropological investigation or for wider clinical applications. This study demonstrates the advantages of MSCT imaging in osteometry, thus recommending its immediate application in forensic anthropological investigations.

Acknowledgments

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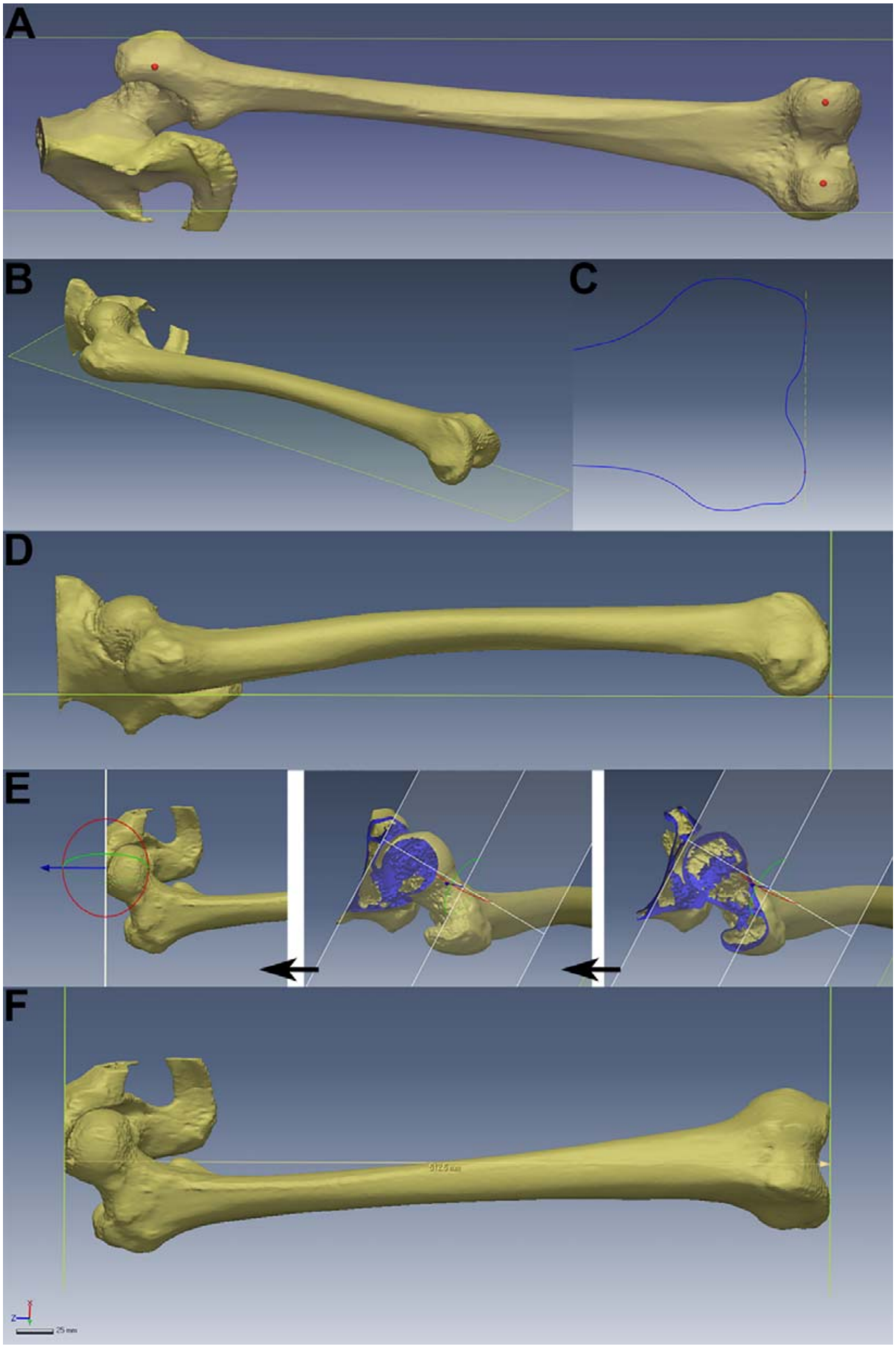

Fig 1. Virtual measurement of long bone length in Geomagic Design X™. (A) A posterior base plane was generated. The dots indicate the user-determined reference points on the most

posterior aspects of the bone. (B) The posterior plane represents the fixed base of an osteometric board. (C) A 3D sketch obtained from a silhouette curve of the external contour of the distal bone (dark outline) and the tangent vector (dashed line) obtained via selecting reference points on the most distal aspect, were used to generate a rotational plane. (D) The distal rotational plane is perpendicular to the base plane, representing the fixed raised edge of an osteometric board. (E) View clip tool was used to identify the proximal boundary of the femoral head within the acetabulum. (F) An offset plane was aligned to the user defined proximal boundary and an automated plane-to-plane measurement was conducted between the rotational plane and the offset plane.

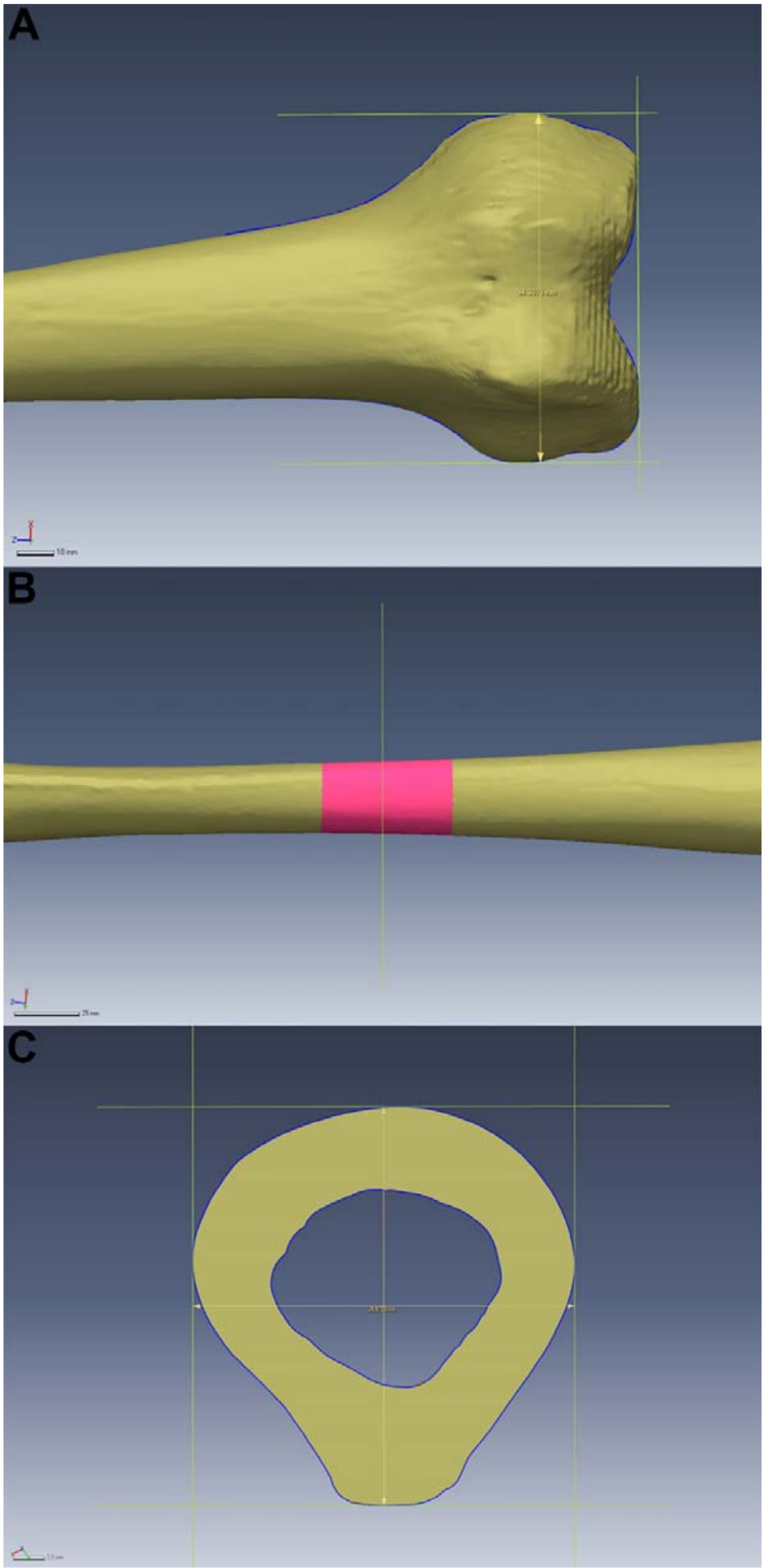

Fig 2. Virtual measurement of long bone breadth and midshaft in Geomagic Design X™.

(A) Automatically generated extreme position planes using the distal 3D sketch and distal rotational plane to conduct an epicondylar breadth plane-to-plane measurement. (B) Midline plane constructed to identify the midshaft transverse section of interest. (C) Automated plane-to-plane measurements taken between the anterior and posterior extreme position planes and the medial and lateral extreme position planes to calculate diameter of midshaft. Cortical area was identified as the area between the periosteal and endosteal 3D sketches.

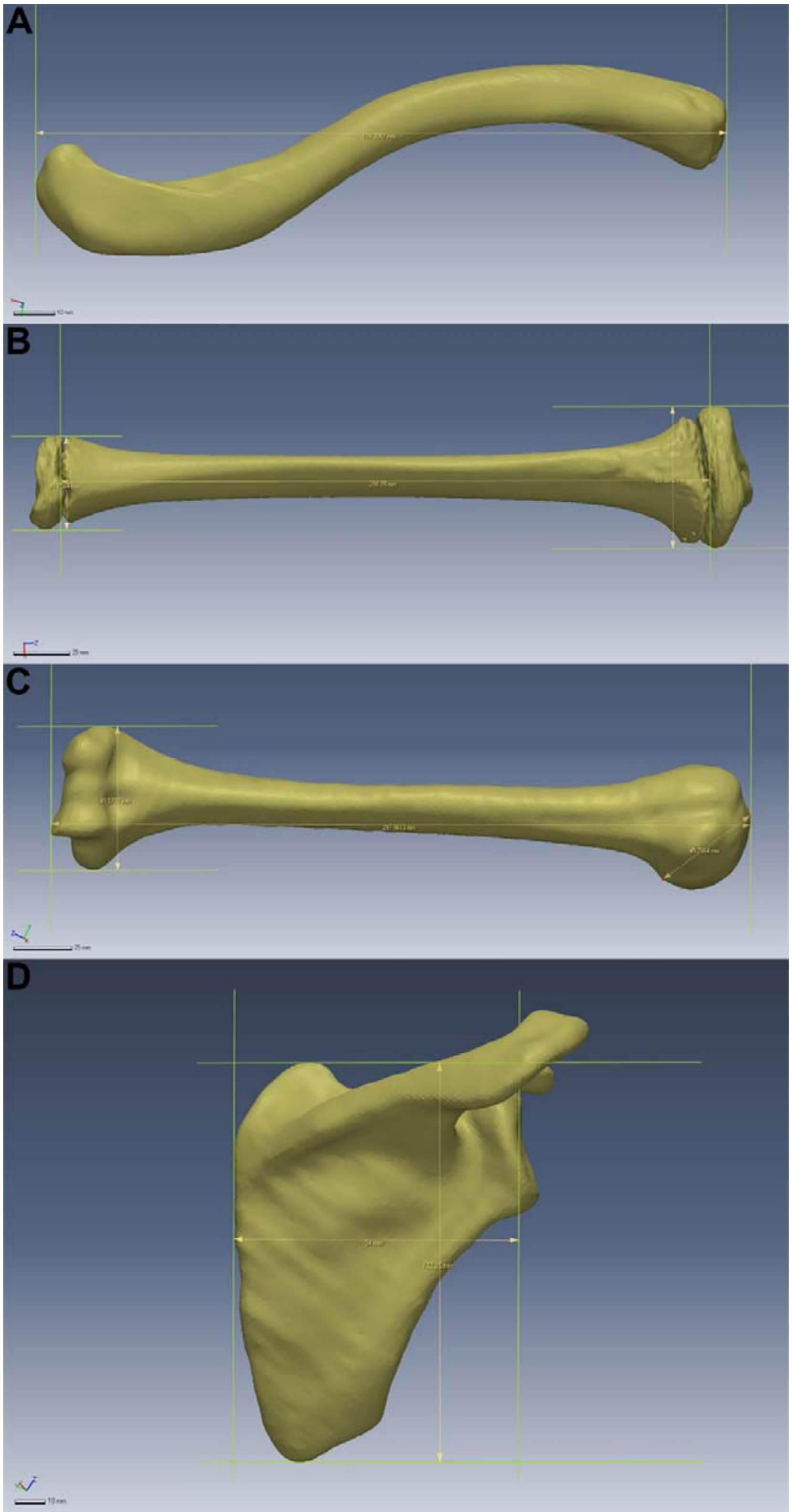

Fig 3. Automated anthropometric assessment of a range of postcranial bones in Geomagic Design X™. (A) Maximum length of the clavicle. (B) Maximum tibial diaphyseal length of

the subadult tibia. (C) Maximum length, epicondylar breadth and diameter of the head of the humerus. (D) Height and breadth of the scapula.

Table 1. Assessment of intra-observer reliability in 3D models using technical error of measurement (TEM), relative TEM (%TEM) and intraclass correlation coefficient (ICC) from repeat measurements of femoral bicondylar length, epicondylar breadth, AP diameter, ML diameter (mm) and cortical area (mm^2) performed by a single observer *(MR)* on six samples on three separate days.

	Measurement (mm)					
Sample	Day 1	Day 2	Day 3	**TEM**	**%TEM**	**ICC (CI)**
Bicondylar length						
1	509	510	510			
2	485	485	486			
3	463	463	463			
4	507	507	508			
5	477	478	478			
6	455	455	454			
Mean				**0.53mm**	**0.11%**	**0.999 (0.998-1.000)**
Epicondylar breadth						
1	90.29	90.22	90.13			
2	89.88	90.06	90.32			
3	91.21	91.22	91.26			
4	86.37	86.60	86.81			
5	88.16	88.43	87.70			
6	89.99	89.83	89.85			
Mean				**0.20mm**	**0.23%**	**0.986 (0.943-0.998)**
AP diameter						
1	37.74	37.45	37.79			
2	31.90	32.11	31.93			
3	35.04	34.97	35.41			
4	35.09	34.65	34.89			
5	35.19	35.21	35.25			
6	34.59	33.97	33.87			
Mean				**0.22mm**	**0.64%**	**0.985 (0.944-0.998)**
ML diameter						
1	29.20	29.20	29.39			
2	29.39	29.70	29.61			
3	28.30	27.79	28.30			
4	30.47	31.60	32.23			
5	32.68	32.57	32.90			
6	29.74	28.85	28.81			
Mean				**0.45mm**	**1.50%**	**0.927 (0.749-0.988)**
Cortical area (mm^2)						
1	517.60	500.65	519.00			
2	503.23	521.89	511.16			

3	528.39	528.39	539.52			
4	586.79	597.22	609.82			
5	653.97	660.51	656.73			
6	596.93	587.86	584.16			
Mean				**8.37mm^2**	**1.48%**	**0.979 (0.922-0.997)**

Table 2. Assessment of inter-observer reliability in 3D models using technical error of measurement (TEM), relative TEM (%TEM) and intraclass correlation coefficient (ICC) for 6 samples from repeat measurements of femoral bicondylar length, epicondylar breadth, AP diameter, ML diameter (mm) and cortical area (mm^2) in Geomagic Design X^{TM} performed by four observers on three separate days.

Measurement	TEM	%TEM	ICC (CI)
Bicondylar Length			
Day 1	2.01	0.42	0.997 (0.989-1.000)
Day 2	2.62	0.54	0.996 (0.985-0.999)
Day 3	3.12	0.65	0.995 (0.978-0.999)
Mean	**2.58**	**0.54**	**0.996 (0.978-1.000)**
Epicondylar Breadth			
Day 1	0.27	0.31	0.994 (0.979-0.999)
Day 2	0.17	0.19	0.997 (0.990-1.000)
Day 3	0.19	0.21	0.997 (0.990-1.000)
Mean	**0.21**	**0.23**	**0.996 (0.979-1.000)**
AP Diameter			
Day 1	0.51	1.46	0.980 (0.930-0.997)
Day 2	1.69	4.98	0.855 (0.527-0.977)
Day 3	0.59	1.72	0.977 (0.864-0.997)
Mean	**0.93**	**2.72**	**0.937 (0.527-0.997)**
ML Diameter			
Day 1	0.89	2.95	0.963 (0.855-0.994)
Day 2	0.70	2.40	0.957 (0.781-0.995)
Day 3	0.74	2.50	0.946 (0.677-0.992)
Mean	**0.78**	**2.62**	**0.955 (0.677-0.995)**
Cortical Area			
Day 1	11.15	1.98	0.993 (0.975-0.999)
Day 2	17.81	3.19	0.980 (0.930-0.997)
Day 3	12.77	2.29	0.986 (0.924-0.998)
Mean	**13.91**	**2.49**	**0.986 (0.924-0.999)**

Table 3. Assessment of inter-observer reliability in dry femora using technical error of measurement (TEM), relative TEM (%TEM) and intraclass correlation coefficient (ICC) for 6 samples from repeat measurements of femoral bicondylar length and epicondylar breadth (mm) on a physical osteometric board, performed by four observers on three separate days.

Measurement	TEM	%TEM	ICC (CI)
Bicondylar Length			
Day 1	0.94	0.26	1.000 (1.000-1.000)
Day 2	0.83	0.19	1.000 (0.999-1.000)
Day 3	1.15	0.27	0.988 (0.958-0.998)
Mean	**0.97**	**0.24**	**0.996 (0.958-1.000)**
Epicondylar Breadth			
Day 1	0.49	0.67	0.997 (0.990-1.000)
Day 2	0.59	0.80	0.996 (0.986-0.999)
Day 3	0.54	0.73	0.997 (0.988-1.000)
Mean	**0.54**	**0.73**	**0.997 (0.986-1.000)**