Technical Note

Standardization and quality assurance in skeletal landmark placement and osteometry

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Keywords: forensic science; forensic anthropology; accuracy; reliability; validation; error

Highlights:

- This study addressed modifications to commonly used osteometric standards
- Several measurements differed significantly using the modified definitions
- Databases and SOP's must be updated to take these modifications into consideration

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ABSTRACT

Studies revising methodology are essential to the development and standardization of the field of anthropology, especially as the ultimate goal is improved forensic analyses. A series of revisions were made to the Standards for Data Collection Procedures reference manual. This includes changes made to the definitions of several standard measurements ranging from modified landmark placement to variation in the proper orientation of the caliper. The aim of this paper was to compare measurements collected using the different sets of definitions to determine if the measurements would differ significantly. Fifteen measurements were collected from 30 crania and postcrania, first using the original definitions, and then using the modified definitions and/or landmarks. The measurement differences for the 2 sets of definitions were assessed using technical error of measurement and a Kruskal-Wallis test. Results indicate that 8 of the 15 measurements differed significantly when the modified definitions were employed. Therefore, data collected using the different sets of definitions should not be used interchangeably. Forensic practitioners and laboratories making use of the updated reference manual must take into consideration how the current results might influence their standard operating procedures. Furthermore, all databases that currently make use of the original measurements, such as the South African-specific databases used in Fordisc, must be updated to include the modified measurements to stay on par with international data collection standards.

Keywords

Forensic science
Forensic anthropology
Accuracy
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Validation
Error

1. Introduction

Physical and forensic anthropologists make use of various methods to address each of the parameters of the biological profile; the methods are typically categorized as morphological or osteometric. In the past the choice and application of these methods was often a matter of personal preference, relying largely on ease of application and how comfortable the practitioner was with the method [1]. The *Daubert* ruling [2] highlighted the importance of sound, robust methodology, something that was lacking to variable degrees in the different sub-disciplines that constitute the field of forensic science. Anthropology was no exception, as many of the traditionally employed techniques lacked rigorous testing and error rates. With the *Daubert* guidelines in place, forensic scientists were required to move towards more sophisticated, quantitative techniques that include strict validation efforts to ensure both precision and validity in the methodology employed in medico-legal casework [3]. A more recent report published by the National Academy of Sciences indicated further aspects pertaining to forensic science that require improvement [4]. As such, anthropologists have completed extensive work to revise and improve current standards, especially for methods assessing the biological profile. Being notorious for numerous methodological issues, the morphological approach to analyzing skeletal variation continues to receive close scrutiny and re-evaluation [e.g. 5 - 7]. On the other hand, the osteometric approach has received less attention in this regard, as the use of standardized equipment and measurement definitions are assumed to be more reliable and repeatable. This assumption is certainly reflected in the literature, as detailed analyses addressing issues with osteometric methodology are fairly limited.

Adams and Byrd [8] presented one of the most prominent studies that explored potential reasons for measurement variability among observers. Their evaluation of a series of postcranial measurements revealed inconsistencies ascribed to confusion surrounding the exact location of certain landmarks, as well as the orientation of the instrument in relation to the bone. For example, how far inferior to the lesser trochanter should the measurement be taken, and should the arm of the caliper be placed flat against the contour of the bone? [8]. A similar study by Smith and Boaks [9] on the cranium also noted major discrepancies in landmark location. For instance, inter-orbital breadth was noted to be taken correctly (as specified by the definition) by only 48% of the study participants [9]. Measurement variability and error culminates in poor repeatability, which ultimately affects the confidence with which skeletal remains can be classified.

In order to minimize the apparent issues associated with osteometry, the standards for data collection procedures (DCP) has been revised from the last version (the third edition) published more than a decade ago [10,11]. The revised DCP presents several modifications to standard measurements. Long bone shaft diameters were changed to measures of minima and maxima rather than position-dependent (e.g. sagittal, transverse etc.) diameters. The definitions for certain measurements (such as the anterior breadth of the sacrum and distal epiphyseal breadth of the tibia) were clarified to be more descriptive. Finally, some measurements, like pubis and ischium length were omitted altogether as the landmarks were simply too difficult to locate and measure consistently [12].

Studies revising methodology are fundamental to the development and standardization of the field as a whole. While the results by Langley et al. [12] demonstrate improved repeatability and greater ease of use, the implications following the changed standards may have unexpected consequences. More specifically, what happens to all of the data collected prior to the proposed changes? The Forensic Data Bank (FDB) is a prime example of the current dilemma. The FDB is a North American initiative that was launched in 1986 to compile a modern forensic database for research. The compiled database contains data from established bone collections (such as the William M. Bass skeletal collection), as well as positively identified forensic cases submitted by forensic anthropologists from numerous laboratories across the United States. The FDB contains information of more than 2000 individuals and is continuously expanded [3]. As data have been consolidated into a universal database since 1986, the measurements would have been collected using older versions of the DCP standards (i.e. the original definitions and landmark locations). Similarly, the first South African cranial database was established in 2013 and consists of coordinate data from modern black, white and coloured South Africans [13,14]. In the last five years, additional observers have added cranial data to the South African cranial database to increase the overall sample size. More recently, a South African postcranial database was also created by Liebenberg et al. [15] and Krüger et al. [16]. Both the cranial and postcranial databases made use of the original DCP standards. There are currently no studies available to demonstrate the margin of error between the original and the new DCP measurements and the potential effect any variation would have on anthropological databases and standards. The aim of this paper is to compare the landmark placement of the modified measurement definitions in the DCP 2.0 for collecting cranial and postcranial measurements to the definitions in the previously published version of the DCP.

2. Materials and Methods

A sample of 30 crania and 30 sets of postcrania were randomly selected from the Pretoria Bone Collection (PBC). As it is beyond the scope of this study to assess sex or ancestry differences, the sex and ancestry of the individual was not taken into account when specimens were selected. The skeletal material in the PBC is derived from cadavers and obtained from either donated or unclaimed bodies received under regulation of the National Health Act 61 of 2003. The remains accessioned into the collection are of documented sex, age-at-death and peer-reported ancestry [17].

The measurements in the different versions of the DCP standards (i.e. original versus modified) were compared to identify any significant differences; this includes 14 measurements (3 cranial and 11 postcranial) that have been modified in the latest version by Langley et al. [11]. In addition, the landmark placement for two different definitions of the nasion-prosthion height measurement were tested. In 1914, Martin provided landmark and measurement definitions that specified the location of prosthion as the most anterior point on the alveolar bone (on the ridge) in the midsagittal plane between the maxillary central incisors, except for when the upper facial height is measured, in which case prosthion is located at the most inferior point on the alveolar bone between the maxillary central incisors [18]. While this definition is not typically used in the DCP manuals, “Martin’s prosthion” is still included as a landmark when digitising crania and can be used to create the measurement abbreviated as UFHT in the FDB. In the current study, UFHT and NPH were also compared to test for significant differences. The measurements explored in the study can be found in Table 1 and Table 2. Each bone was measured twice using a standard sliding caliper and a spreading caliper. First, each measurement was taken using the original definitions and then the measurements were repeated using the modified definitions. The two sets of measurements were compared using a Kruskal-Wallis test to identify any significant differences between the two sets of measurements. Furthermore, absolute and relative technical error of measurement (TEM and %TEM) was calculated to gauge the magnitude of the differences between the two datasets. For the postcranial measurements the original and modified measurements were compared where the overall difference was the smallest. For example, the radtvd measurements were more similar to radmxd than to radmwd and so radtvd was compared to radmxd and tested for significance in the measurement differences. Inter- and intra-observer agreement was also gauged with TEM and %TEM using a sample of 5 randomly selected specimens. The repeatability of both the original and the modified measurements were assessed.

TABLE 1 – The original measurements and their associated abbreviations, taken from Moore-Jansen et al. [10].

Measurement	Abbreviation	Definition
Basion-nasion length	BNL	Direct distance in midsagittal plane between basion and nasion. Basion is located at midline point on the anterior margin of the foramen magnum. For basion-nasion and basion-prosthion measurements, point is located on most posterior point on foramen's anterior rim and is sometimes distinguished as endobasion. Nasion is located at the point of intersection between the frontonasal suture and the midsagittal plane.
Basion-prosthion length	BPL	Direct distance in midsagittal plane between basion and prosthion. Prosthion is located at most anterior point in midline on alveolar processes of the maxillae. Basion location as for BNL.
Upper facial height	UFHT	Direct distance in midsagittal plane between nasion and prosthion. Prosthion, in this case, is located on the most inferior point on the alveolar bone between the central incisors. Nasion location as for BNL.
Mastoid height	MDH	Vertical projection of mastoid process below and perpendicular to eye-ear plane, with fixed arm of caliper tangent to upper border of the external auditory meatus, pointing to lower border of orbit. Slide the measurement arm until level with tip of mastoid.
Clavicle vertical midshaft diameter	clavrd	Superior-inferior distance of midshaft surface.
Clavicle sagittal midshaft diameter	claapd	Anterio-posterior distance of midshaft surface.
Radius A-P midshaft diameter	radapd	Diameter of midshaft in anterio-posterior plane.
Radius transverse midshaft diameter	radtvd	Diameter of midshaft in medio-lateral plane, perpendicular to A-P diameter
Ulna dorso-volar diameter	ulndvd	Maximum diameter of diaphysis where crest exhibits greatest development. Take note, this measurement is not necessarily midshaft
Ulna transverse diameter	ulntvd	Diameter taken perpendicular to dorso-volar diameter at the level of greatest crest development
Ulna physiological length	ulnphl	Distance between deepest point on surface of the coronoid process and lowest point on the inferior surface of the distal head. Take note, caliper should be placed on head, not in groove between head and styloid process
Femur A-P midshaft diameter	femmap	Anterio-posterior diameter taken at midpoint of the diaphysis at the highest elevation of linea aspera
Femur transverse midshaft diameter	femmtv	Transverse diameter taken perpendicular to the A-P diameter at midpoint of the diaphysis
Tibia maximum diameter at nutrient foramen	tibnfx	Distance between the anterior crest and post surface of diaphysis at the level of the nutrient foramen. Take note, bone should be rotated to obtain the maximum
Tibia minimum diameter at nutrient foramen	tibnft	Transverse diameter of diaphysis at the level of the nutrient foramen, taken perpendicular to the maximum diameter

TABLE 2 – The modified measurements and their associated abbreviations, taken from Langley et al. [11].

Measurement	Abbreviation	Definition/Modification
Basion-nasion length	BNL2	Distance from nasion to basion. Basion is located at point at which the anterior border of the foramen magnum is intersected by mid-sagittal plane opposite nasion. Nasion is located at intersection of the naso-frontal suture and the midsagittal plane (on the frontal bone).
Basion-prosthion length	BPL2	Distance from basion to prosthion. Prosthion is located at most anterior point on alveolar bone between central incisors in the midsagittal plane. Basion location as for BNL2.
Upper facial height	NPH	Nasion to prosthion. Nasion and prosthion locations as for BNL2 and BPL2.
Mastoid height	MDH	Direct distance between porion and mastoidale, with caliper in coronal plane. Zygomatic arch is no longer used as a guide.
Maximum diameter of clavicle at midshaft	clavmxd	Maximum diameter of clavicle measured at midshaft; place caliper on bone and rotate until maximum is located. Measurement is a maximum, no longer dependent on position.
Maximum diameter of clavicle at midshaft	clavmwd	Minimum diameter of clavicle measured at midshaft; place caliper on bone and rotate until minimum is located. Measurement is a maximum, no longer dependent on position.
Maximum diameter of radius at midshaft	radmxd	Maximum diameter of radius taken at midshaft. Measurement is a maximum, no longer dependent on position
Minimum diameter of radius at midshaft	radmwd	Minimum diameter of radius taken at midshaft. Measurement is a maximum, no longer dependent on position.
Maximum diameter of ulna at midshaft	ulnmxd	Maximum diameter of ulna at midshaft. Measurement is a maximum, no longer dependent on position. Now taken at midshaft.
Minimum diameter of ulna at midshaft	ulnmwd	Minimum diameter of ulna at midshaft. Measurement is a maximum, no longer dependent on position. Now taken at midshaft.
Physiological length of the ulna	ulnphl2	Distance between deepest point on articular surface of coronoid process on guiding ridge and most inferior point on distal articular surface
Maximum diameter of femur at midshaft	femmxd	The maximum diameter of femur taken at midshaft. Measurement is a maximum, no longer dependent on position.
Minimum diameter of femur at midshaft	femmwd	The minimum diameter of femur taken at midshaft. Measurement is a maximum, no longer dependent on position.
Maximum diameter of tibia at midshaft	tibmxd	The maximum diameter of tibia taken at midshaft. Measurement is a maximum, now taken at midshaft and not at the location of the nutrient foramen.
Minimum diameter of tibia at midshaft	tibmwd	The minimum diameter of tibia taken at midshaft. Measurement is a maximum, now taken at midshaft and not at the location of the nutrient foramen.

3. Results

Intra-observer error rates for the original measurement definitions ranged from 0.00 to 0.91 (TEM) and 0.00 to 4.52% (%TEM), with the largest TEM error rate noted for NPH and the largest %TEM noted for ulndvd. Similarly, for the inter-observer error, rates ranged from 0.00 to 1.00 (TEM) and 0.00 to 4.65% (%TEM), with the largest error rates noted for MDH and ulntvd for TEM and %TEM, respectively (Table 3). The intra-observer error rates for the modified measurements ranged from 0.00 to 0.82 (TEM) and 0.00 to 2.61 (%TEM), with the largest error rates noted for MDH (TEM and %TEM) and clamxd (%TEM only). Furthermore, for the inter-observer error, the rates ranged from 0.00 to 1.34 (TEM) and 0.00 to 4.04 (%TEM), with the largest difference note for the MDH measurement (Table 4).

TABLE 3 - Intra- and inter-observer error rates when assessing 15 cranial and postcranial measurements taken using the original measurement definitions*.

	Intra-observer			Inter-observer		
	TEM	Mean (mm)	%TEM	TEM	Mean (mm)	%TEM
BNL	0.39	102.6	0.38	0.45	102.3	0.44
BPL	0.47	100.1	0.47	0.82	100.6	0.81
UFHT†	0.91	67.4	1.35	0.71	67.6	1.05
MDH	0.74	30.2	2.45	1.00	30.3	3.30
clavrd	0.00	10.3	0.00	0.00	10.4	0.00
claapd	0.35	11.7	3.58	0.00	11.9	0.00
radapd	0.00	12.1	0.00	0.45	11.8	3.99
radtvd	0.00	14.6	0.00	0.45	14.7	3.29
ulndvd	0.63	16.0	4.52	0.55	15.0	3.94
ulntvd	0.00	14.4	0.00	0.63	14.5	4.65
ulnphl	0.00	225.9	0.00	0.61	225.7	0.27
femmap	0.00	28.7	0.00	0.32	28.9	1.15
femmtv	0.00	26.4	0.00	0.55	26.2	2.27
tibnfx	0.00	34.6	0.00	0.32	34.2	0.97
tibnft	0.52	24.5	1.38	0.45	24.3	1.96

*definitions taken from Moore-Jansen et al. [10].

†definition taken from Martin [18].

TABLE 4 - Intra- and inter-observer error rates when assessing 15 cranial and postcranial measurements taken using the modified measurement definitions*.

	Intra-observer			Inter-observer		
	TEM	Mean (mm)	%TEM	TEM	Mean (mm)	%TEM
BNL	0.55	97.6	0.56	0.32	97.8	0.33
BPL	0.55	98.6	0.56	1.00	99.4	1.01
NPH	0.00	63.4	0.00	0.45	63.4	0.71
MDH	0.84	32.0	2.61	1.34	33.2	4.04
clamxd	0.32	12.1	2.61	0.45	12.2	3.67
clamwd	0.00	9.4	0.00	0.00	9.4	0.00
radmxd	0.32	14.5	2.18	0.00	14.4	0.00
radmwd	0.00	11.0	0.00	0.00	11.0	0.00
ulnmxd	0.32	15.5	2.04	0.32	15.5	2.04
ulnmwd	0.00	11.2	0.00	0.00	11.2	0.00
ulnphl2	0.45	221.0	0.20	0.45	221.0	0.20
femmxd	0.45	28.6	1.56	0.32	28.5	1.11
femmwd	0.32	22.1	1.43	0.32	22.1	1.43
tibmxd	0.45	27.4	1.63	0.55	27.5	1.99
tibmwd	0.32	20.3	1.56	0.00	20.4	0.00

*definitions taken from Langley et al. [11].

Kruskal-Wallis was used to gauge the disparities in measurements when different definitions were used. In the cranial measurements, only the nasion-prosthion measurements (NPH and UFHT) differed significantly between landmark definitions with an absolute TEM of 2.56. Although, as the overall size of the measurement was relatively large, the %TEM was only the second highest (3.77%), behind MDH, which had a %TEM of 4.51% (Table 5). When the postcranial shaft measurements were compared, 7 of the 11 measurements showed significant differences between the position-dependant diameters and the midshaft maxima and minima (Table 6). Absolute TEM for the postcranial measurements revealed the largest differences between the tibial measurements (tibnfx vs. tibmxd and tibnft vs. tibmwd) and the ulnphl measurements. However, the %TEM results were large (greater than 5%) for the majority of the measurement comparisons (8 of 11). While the comparisons of the physiological lengths of the ulna displayed a large absolute TEM, the difference was small when the overall size of the measurement was considered (%TEM of 1.72). The measurement differences with the smallest %TEM included the ulnphl-ulnphl2, radapd-radmwd, and femmap-femmxd comparisons.

TABLE 5 - Kruskal-Wallis, TEM and %TEM results when comparing cranial measurements taken using the original definitions* and taken using the modified definitions†.

Measurements compared	Mean (mm)	Standard deviation	Kruskal-Wallis p-value	TEM	%TEM
BNL	101.47	5.02	0.835	0.66	0.65
BPL	101.25	7.26	0.505	1.16	1.15
NPH-UFHT‡	67.80	5.28	**<0.01**	2.56	3.77
MDH	31.63	3.72	0.334	1.43	4.51

*definitions taken from Moore-Jansen et al. [10]

†definitions taken from Langley et al. [11].

‡definitions taken from Martin [18].

TABLE 6 - Kruskal-Wallis, TEM and %TEM results when comparing postcranial shaft measurements taken using the original definitions* and taken using the modified definitions†.

Measurements compared	Mean (mm)	Standard deviation	Kruskal-Wallis p-value	TEM	%TEM
clavrd - clamwd	9.87	1.93	**0.025**	1.49	15.15
claapd - clamxd	11.70	1.66	**0.039**	0.97	8.26
radapd - radmwd	11.38	1.71	**0.040**	0.90	7.94
radtvd - radmxd	14.60	2.16	0.875	0.41	2.80
ulndvd - ulnmxd	15.35	2.28	0.228	0.83	5.39
ulntvd - ulnmwd	12.61	2.11	**<0.01**	1.78	14.14
ulnphl – ulnphl2	224.30	19.76	0.679	3.86	1.72
femmap - femmxd	28.93	3.55	0.705	0.58	2.00
femmtv - femmwd	25.00	3.02	**<0.01**	1.92	7.69
tibnfx - tibmxd	31.32	4.52	**<0.001**	4.25	13.58
tibnft - tibmwd	22.75	4.15	**<0.001**	3.15	13.84

*definitions taken from Moore-Jansen et al. [10].

†definitions taken from Langley et al. [11].

4. Discussion and conclusion

This study aimed to determine if measurements collected using definitions from the latest version of the DCP would differ significantly from measurements collected using the definitions from the previous published version. Overall, the TEM results for both original and modified measurements were fairly similar, with a few measurements presenting with greater levels of disagreement. More specifically, for the original measurements radapd, radtvd, ulndvd, ulntvd and MDH demonstrated a %TEM greater than 3%. The modified measurements presented with slightly better agreement; however, clamxd, and once again radmxd, ulnmxd and MDH presented with greater error. The modified MDH notably produced a higher %TEM than the original measurement. One potential reason for this discrepancy is user experience. Even though the modified measurements are overall easier to take, the authors have more extensive experience working with the original definitions. With increased experience and familiarity with the modified definitions the error-rate may be lower.

While there is no universally agreed upon cut-off point for measurement error, Perini et al. [19] recommend that the margin of error between observers should be lower than 2%. However, this is not always practically possible, as the margin of error largely depends on the size of the measurement. Essentially, measurement error will have a greater impact on smaller measurements, even if the error itself is not particularly large. For example, with the inter-observer results for the modified measurements a 0.45mm discrepancy for clamxd resulted in a %TEM of 3.67%, while the same discrepancy for ulnphl2 only resulted in a %TEM of 0.20%. Thus, when assessing measurement error it is important to also take into consideration the size of the measurement (as is done with %TEM) to provide a more realistic report of the practical implications of the measurement error. Despite some discrepancies, the modified measurements were found to be sufficiently repeatable and in some instances more repeatable than the original definitions, confirming the results of Langley et al. [12]. The measurement modifications were discussed during a workshop held by the Forensic Anthropology Interest Group (FAIG) at the annual meeting of the Anatomical Society of Southern Africa (ASSA) in 2019. The majority of the participants, consisting of practitioners with varying levels of experience, commented that the modified measurements were more comfortable to take, and that they would prefer to use the definitions in future. With promising repeatability and a favourable reception from the anthropology community in South Africa, we recommend that the latest DCP reference manual with the modified definitions be used to conduct anthropological analyses.

Unfortunately, the Kruskal-Wallis test results indicate that numerous measurement differences between the two sets of definitions or different landmark placements would need to be addressed. The majority of the discrepancies were observed with the postcranial variables, with %TEM differences as high as 15.15%. It should be acknowledged that even the variables that were not statistically significantly different ($p > 0.05$), demonstrated fairly high %TEM values. Thus, data collected using the different sets of definitions cannot be used interchangeably. For the cranium, BPL, BNL and MDH did not yield significant differences. However, there is a significant difference between the upper facial measurements that make use of either Howells' or Martin's prosthion (i.e. NPH versus UFHT, respectively). As such, while UFHT is present in the databases based on digitized crania (such as the South African cranial database), UFHT should not be selected in Fordisc analyses that otherwise make use of linear measurements with definitions as presented in the DCP manuals (i.e. using

Howells' prosthion). Overall, while some variables could technically be used interchangeably regardless of how the measurement was taken, best practice dictates consistency among practitioners and researchers and therefore leads to the suggestion that the new DCP be implemented in all laboratories. However, this does require forensic practitioners and laboratories to revise their standard operating procedures and data collection procedures, and for South African practitioners to change current databases to include the modified measurements.

CRediT authorship contribution statement

Leandi Liebenberg: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Project administration. **Gabriele C. Krüger:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - review & editing.

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