Real or Replicated: The use of human remains as pedagogic resources in forensic anthropology higher education

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Abstract: Forensic anthropology is a staple of forensic undergraduate programs; however, resources used for education are not standardized across institutions, with student provisions varying by type and quality of materials. Using real human skeletal material will always have the greatest benefits when learning forensic anthropology, but as the results of this study suggest, access to other types of resources could also have a positive impact. In total, 56 students participated across three workshops, using real and/or replicated skeletal material. Mann-Whitney *U* tests determined the level of student engagement with the material. With results showing significant differences between the groups using real and replicated skeletal material, indicating that real human remains were more beneficial for learning and understanding. However, the results taken from the third workshop suggest participants felt more confident having had access to both real and replicated skeletal material. Although the use of real skeletal material proved more beneficial to the participant's learning and understanding, the overarching response, even from students who did not have access to replicated material, was that replicated material should be included in forensic anthropology education, even if just for learning the basics of skeletal anatomy. Students believed that the use of highly durable cast material could allow for greater physical interaction with the material without the worry of causing damage, potentially meaning students can gain a better hands-on experience. In which case, having access to a greater range of physical material in forensic anthropology education could prove highly valuable for student learning and engagement.

Keywords: Anthropology - Forensic Pedagogy - Human Bones - Pedagogic Resources - Skeletal Material

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Introduction

The use of human remains as teaching materials has a long history, spanning hundreds, if not thousands, of years (1,2,3). However, this has predominantly been within a medical perspective, where the objective is to understand the human body better to aid in treating the living. Within the subject of forensic science, more specifically forensic anthropology, their use has a much shorter timeline (4,5). In the United States, the first forensic anthropology case can be traced back to 1949 (6, 7), however in the United Kingdom, the first documented forensic anthropology case did not take place until nearly a century later in 1935 (8,6). It was only after realizing the usefulness of calling on anatomists to assist within police investigations that forensic anthropology became a specific subject.

Many instances negate for the use of forensic investigation into the identity of an individual and can encompass varied states of wholeness and decomposition. These include the discovery of clandestine burials (9), mortality rates as a result of mass disasters (10,11) and where an individual may have died alone at home (12). In any forensic case, it is essential that any human remains found can be correctly identified (13,14). In a mortuary setting, before expensive procedures such as DNA profiling are undertaken, initial studies on remains must be carried out. These can include assessing the state of preservation, noting distinguishing marks or features, and assessing whether individuals can definitively be identified without the need for additional, costly processes (15,16). However, in the field, when forensic professionals encounter human remains, it is necessary to have an all-encompassing knowledge to understand what they have been presented with. It is easy to determine a recently dead individual who has not been subject to the full process of decomposition, but in instances when all that are left are skeletal remains, it is vital to understand what is present, and whether an initial profile of the individual can be made (17,18). Further to this, it is crucial to be able to distinguish between human and non-human skeletal remains so as to not waste valuable practitioner time or resources (19,20,21). It is essential that students are taught the methodologies alongside the best possible pedagogic resources, so that if they want to enter this field post-education they have a good enough understanding and enough hands-on experience. In a learning environment it is possible to have access to a

wide range of resources, including books, digital material and a physical reference collection, however, when students complete their education and move into the professional world, this resource collection is not as comprehensive whilst out in the field. This means that having a greater variety of pedagogic resources, and the ability to interact with physical material whilst in education, could create a significant knowledge base for when students enter professional environments.

Skeletal Material in Education

Osteoarchaeology and forensic anthropology cover much of the same subject matter, including how to estimate skeletal sex, create an age-at-death profile, estimate stature, look for pathology and determine taphonomic impact (4). However, the amount of time that is spent on each topic, and the type of material which is used as a resource may not be uniform across subjects or even institutions. In a recent study undertaken by the authors (22) it was identified that not all universities in the United Kingdom which include forensic anthropology as part of their undergraduate forensic science programs provide access to real human skeletal material as a teaching aid. Students are instead being taught using replicated skeletal material; from less expensive, lower grade plastic teaching skeletons, to more expensive 3D printed and cast skeletal material. This often means that students are taught the methodologies of skeletal identification without having access to real skeletal material, whilst other universities may only have access to real and no replicated material, which could initially be seen as advantageous (23).

Numerous studies have been conducted on the importance of problem-based learning (24,25) and the use of a hands-on approach when learning within forensic science (26,27). The consensus formed by these studies is that the use of interactive material significantly enhances learning potential through the ability to interact with and manipulate physical resources. However, they do not necessarily suggest one type of physical resource as superior to another, only that the greater the number of resources a student has access to, the greater their ability to learn. Identifying whether having access to replicated material is satisfactory, and/or if using only real or a mixture of replicated and real skeletal remains is advantageous, is therefore of importance to investigate.

At Keele University, where this study was conducted, the undergraduate forensic anthropology module (as of the 2024/25 academic year) is covered in the second year and comprises ten weeks of lectures and practical sessions. In this instance, replicated material is used within the first few weeks for learning basic skeletal anatomy (identifying types of bones, learning the anatomical layout etc) and about the ethical implications which come with studying and handling human remains, before any real skeletal material is introduced. Each week concentrates on a different topic, including those as noted above, but also how to identify types of trauma (ante, peri and post mortem) and dental anthropology. As this ten-week period is a relatively short timeframe within the three-year degree programme, with many detailed aspects to learn, focus on some of the simpler points might be lost. One of the first things taught on this module is the composition of bone, including formation and how it can repair itself. This is learned predominantly on a screen rather than by in-depth examination of physical material where students would be able to see and get a feel for the textures of human bones. For students undertaking this module, the emphasis is on creating enough information to identify an individual, meaning that perhaps some of the most basic, but highly important areas of study, such as the ability to simply identify bone, are missed. Even more so if students begin with replicated material, and then move on to specific topics with real material before learning to fully appreciate the difference between the two.

There are a number of very clear differences between real and replicated skeletal material, and it could be said that there are also additional differences according to the types and/or brands of replications. There are varying grades of quality, from basic plastic replications which can be bought cheaply from Amazon (https://www.amazon.co.uk) and eBay (https://www.ebay.co.uk), to highly detailed, much more expensive, 1-1 exact scale casts such as that made by US based Bone Clones® (https://boneclones.com). Although there is now the ability to create high quality replica material, cast material has yet to fully replicate certain aspects of bone, including the weight and density, visual appearance and physical texture. There is a distinct difference in appearance in real bone between that of the exterior compact bone, and of the porous interior trabecular bone, meaning that when there is an accidental break or an intentional cross-section of a real bone, and the interior is exposed, an obvious difference should be observed. This, however, is impossible to recreate in replicated skeletal material. Although real bones can be cast, and now 3D printed, it is impossible to replicate the difference between the compact and the trabecular bone, and the definition of some other highly detailed features (i.e. 28,29,30). Examples of both real and replicated skeletal material can be seen in **FIGURE 1**, which aims to show the distinct difference between the two resources. The quality and detail mark an extreme difference between real and replicated material which could potentially cause problems for students who only have access to replicated material as part of their studies.

FIGURE 1 Damaged long bones, showing the difference between Real and Replicated skeletal material. The Real bone on the left shows the differences in texture and visual appearance between the smoother, exterior compact bone and the spongy, interior trabecular bone. The Replicated bone on the right shows no difference between the exterior and interior; the smoothness on the outer surface continues on the inside, where the diaphysis is completely hollow.

When creating an age-at-death profile for a set of skeletal remains, surface texture proves invaluable. While the use of texture is not necessarily needed in the aging of children (as there are more accurate ways including dentition and the fusion of growth plates), the auricular surface and the pubic symphysis play a large part in the aging of adult individuals through surface degradation (31,32,33). In which case, if students only have access to replicated skeletal material it must be extremely detailed to provide the same inferences as real skeletal material. It could be argued that students have a series of specific methodologies to follow for creating age-at-death profiles, including the Suchey-Brooks method (34) for the pubic symphysis, and Lovejoy et al (35) for the auricular surface, so perhaps are more likely to identify those features. Certain characteristics, such as billowing of the pubic symphysis in younger adults, and later, exterior lipping in aging individuals can be quite pronounced, and so are possibly easier to replicate than other, more subtle features. As these areas are so important, more time and greater detail might be put into their casting and replication, meaning that students who might only have access to replicated skeletal material would perhaps not be at such a disadvantage as their counterparts who have access to real skeletal material.

Aims of this Study

The main focus for studies undertaken on the use of human remains as teaching materials reside within anatomical teaching, predominantly for teaching subjects related to the biomedical sciences (i.e. 36,37,38). For centuries, the overarching theme for the use of human remains as teaching materials has been from a medical perspective - to further understand the human body and how to treat the living. Other subjects which also include human remains education have much less, if any, literature. For example, the determination as to what are the most useful pedagogic resources in archaeology education has extremely limited literature (39). Further to this, research into the viability and educational benefit of using real and replicated human skeletal material whilst teaching undergraduate students forensic anthropology appears non-existent. Although it is possible to cross-examine the results from similar subjects, it is of course more beneficial to undertake subject-specific studies, which will provide a greater insight into what resources students find most useful for their learning processes.

The intention of this study is to assist in understanding what materials students find help them the most during their forensic anthropology education as part of their undergraduate degree program. As stated above, many institutions only have access to plastic and cast material for teaching, whilst others have access to both real and replicated material (22). Even though the use of formative assessment is valuable for both evaluating the teaching program, and the learning outcomes of the participating students (40), it was decided not to formally assess students on their abilities, and instead directly ask what resources they preferred to use and why. The reasoning behind this was so that students could move at their own pace (41) and take as much or as little time at each station as desired without feeling the pressure of having to pass a test (42). Investigating what students prefer to use for different aspects of their learning and why could be beneficial for the teaching process, allowing for greater engagement and better interaction with the physical material, and making the subject matter easier to understand.

To support this approach, while participants were not formally assessed within any of the workshops, great care was taken to interact with them during the workshops. This interaction included asking questions about participant's prior knowledge and their opinions on the types of material used to teach forensic anthropology. It also included asking some of the questions included in the handouts, getting participants to identify certain skeletal markers (such as the sharpness of the supraorbital ridge, the width of the pubic angle, and the degree of billowing on the pubic symphysis). This was done to make sure that participants were confident in which features they were looking for, and how to interpret them. This also ensured

that all participants, upon completing their feedback form, were aware of the correct answers and approaches to all aspects of skeletal analysis covered in the workshops, and understood how correct assessments would be made in the field.

Materials and Methods

In order to identify the most informative and effective way of teaching forensic anthropology to forensic undergraduate student surveys were run across three separate and distinct workshops. The first workshop used only real skeletal material for students to interact with, the second used only replicated material, and the third used both the same real and the replicated material used across the two previous workshops. These workshops were arranged at Keele University for the second-year (UK level 5) undergraduate forensic science students within their timetabled classes, and each lasted 3 hours. These students were nearing the end of the 10-week forensic anthropology module and had already been taught how to complete a skeletal sex estimation and age-at-death profile as part of their learning. Before conducting the workshops, ethical approval was sought from the university.

Before each workshop an introductory presentation was delivered. This began with a brief insight into the reasoning for undertaking the workshops and aims for subsequent research. Next was a basic introduction to bone as a hard tissue, including composition, structure and durability. There was then subsequent discussion in more detail on the key skeletal markers which would be looked at as part of the workshop. This included how to create an age-at-death profile and a skeletal sex estimation, by identifying specific features within the bone.

At the end of the introductory presentation, before beginning any interaction, ethical implications were also discussed. Although participants had already undertaken study on the ethics of using real human remains as part of the forensic anthropology module, specific care was taken to ensure that this point was reiterated. Comments were made on the provenance of remains used, alongside their fragility and inability to replace or effectively repair should any damage be done. By reminding participants of the ethical implications of handling and studying human remains, it was hoped that participants would remember this in any future interactions, thus fostering good professional practice. Participants were also reminded that ethical polices regarding the handling of human remains are ever changing (43,44,45,46), and so it would serve participants well to keep up to date with changing policies if continuing in human remains education or if going into the field. It is also worthy to note that the participants of the first and third workshops were advised that they did not have to handle any real skeletal material if they did not feel comfortable to do so.

Each of the three workshops had four stations; the first to determine skeletal sex using the skull; the second to determine skeletal sex using pairs of os coxae; the third to determine an age-at-death profile based on individual os coxa; the final station focused on sensation – the texture, visual aesthetic and weight and density. Each station comprised of three resources selected to be significantly different from each other. For the skeletal sex estimation using the skull (for both real and replicated material) an individual was selected showcasing masculine to hyper masculine features, another selected to showcase feminine to hyper feminine features, and the third was selected based on a range of both possible masculine and possible feminine features to show human diversity. The os coxae were chosen using the same principles, with one pair showing masculine traits, a second pair showing feminine traits and the final pair showing a combination of the two. For the age-at-death profile a single os coxa was selected from three individuals; a younger adult, an older adult and one in the mid-range was selected for the real material, while a selection of cheaply made and more expensive, anatomically correct, material was used for the replicated workshop – focusing more on the quality of resources than a specific selection of ages. The final workstation comprised a series of long bones to show the surface texture, the interior structure and the density of real bone, while the replicated workshop comprised three long bones which should show the same traits but were not able to because of the replication process. Photographs of the material used can be seen in **FIGURES 2 and 3**.

FIGURE 2 Samples of the real skeletal material used in Workshops 1 and 3. Top – Bottom: Real skull used in Workstation 1 – Sex Estimation; Real pelvic bones used in Workstation2 – Sex Estimation (Left); Real os coxa used in Workstation 3 – Age Estimation (Right); Real damaged long bone used in Workstation 4 – Visual Appearance and Tactile Feel.

FIGURE 3 Samples of the replicated skeletal material used in Workshops 2 and 3. Anticlockwise Top Left – Top Right: Replicated skull used at Workstation 1 – Sex Estimation. High quality cast purchased from Bone Clones®; Replicated pelvic bones used in Workstation 2 – Sex Estimation; Replicated os coxa used in Workstation 3 – Age Estimation. Cheaper, lower quality disarticulated skeleton; Replicated damaged long bone used in Workstation 4 – Visual Appearance and Tactile Feel.

Each student was provided with a handout (see Supplementary Material) giving information on creating an age profile or sex estimation based on the physical material they had access to. They were also encouraged to look at textbooks and/or digital content for extra reference (such as White and Folkens' The Human Bone Manual). The handouts included space to record students' estimation of skeletal sex, age-at-death and their interpretation of sensation.

After participants had completed their worksheets and were satisfied with the time they had to access the physical material, surveys were distributed. For the real and the replicated workshops the same survey was used. The only signifying difference was a letter printed on the top right-hand corner of the survey papers ("R" for real skeletal material and "F" (Fake) for replicated skeletal material), so the papers would not be confused during subsequent analysis. The survey for the third workshop, using both real and replicated skeletal material, was double the length, asking participants to take into consideration the real and the replicated material as two separate resources. All surveys comprised a series of Yes/No questions, Likert scale questions and the option for descriptive answers. Worthy of note is the wording

used for the Likert questions. For sex estimation and age estimation, participants were asked how confident they felt in the profiles that they had created, however, relating to haptic sensation and visual texture, participants were asked how confident they would feel in their ability to identify real skeletal material in the future based on the material they had access to in their workshop. The full list of questions (some of which have not been addressed here) can be found in the Supplementary Material.

Statistical Analysis

A series of Mann-Whitney *U* tests were run to determine differences in opinion between the use of real skeletal material and replicated skeletal material. The data was analysed across five categories: Sex Estimation, Age Estimation, Visual Appearance, Tactile Feel and Weight and Density.A significance threshold was set at 0.05. This non-parametric test was chosen due to only testing between two groupings – real and replicated. To compare data across all three workshops, the scores given in Workshop 1 (using real skeletal material) were combined with the scores relating to real material collected from Workshop 3 and the scores given in Workshop 2 (using replicated skeletal material) were combined with the scores relating to replicated material from Workshop 3. Statistical analysis was conducted using SPSS v.29. Additional Yes/No answer questions were not statistically calculated through SSPS, and were instead calculated as percentages using Microsoft Excell. This type of question was not compared between groups, but instead calculated across the entire participant population.

Breakdown of Respondents

In total, 56 undergraduate students completed one of the workshop surveys, accounting for 100% of attendees. The first workshop, with only real skeletal material, comprised 22 participants, the second, using only replicated skeletal material, comprised 19 participants, and the final workshop, using both real and replicated skeletal material, comprised 15 participants. It must be noted that Participant 25, from Workshop 2, did not complete the back of the question paper and so has been removed for some questions. No personal information, such as age or gender was requested, as these were deemed irrelevant for this study. Of the 56 participants, only two had completed any osteological training outside of their degree programme, accounting for 3.57% of participants.

Results

In order to fully analyze the data, the results were collated into three separate groupings for statistical analysis. Group A results compare the data obtained in Workshop 1 - using real skeletal material - and Workshop 2 - using replicated skeletal material. Group B results compare the data from all three workshops; the results from Workshop 1 have been combined with the results of the real skeletal material of Workshop 3, and the results of Workshop 2 have been combined with the results of the replicated skeletal material of Workshop 3 to make a larger data set for comparison. Finally, Group C results compare only the results provided by the participants of Workshop 3 who had access to both real and replicated skeletal material.

Group A – Comparing the First and Second Workshops

TABLE 1 shows the results of the Mann-Whitney *U* tests run between participants who undertook the first workshop, using real skeletal material, and the second workshop using replicated skeletal material. No statistical differences were seen in the scores given by participants for either Sex Estimation, or for Age Estimation, but statistical differences were seen within the latter three categories. These three categories all show the same minimum and maximum participant scores (1-10), with Visual Appearance achieving a mean value of 6.63, Tactile Feel a mean value of 6.47 and Weight and Density a mean value of 5.15. All three of these categories show *p*-values of <0.01.

TABLE 1 Comparing the First and Second Workshops. Workshop 1 – real skeletal material, Workshop 2 – replicated skeletal material.*p <.01.

B**Grouping**	**n**	**Min**	**Max**	**Mean**	**SD**	**Mann-Whitney *U* sig.**
Sex Estimation	40	6.00	10.00	8.07	1.04	0.31
Age Estimation	40	3.00	9.00	6.65	1.18	0.05
Visual Appearance	38	1.00	10.00	6.63	2.30	**0.00***
Tactile Feel	38	1.00	10.00	6.47	2.45	**0.00***
Weight and Density	38	1.00	10.00	5.15	2.41	**0.00***

looking further at the data, for sex estimation the participants who only had access to real skeletal material had a smaller range of scores (6-9) than those who only had access to replicated material (6-10). Although the range of scores was lower for real material, a higher maximum figure was noted for replicated material. Additionally, the mean value (seen in **TABLE 4**) calculated for Workshop 2 was higher than that for Workshop 1 (8.44 and 7.77 respectively). Regarding Age Estimation, participants who only had access to real skeletal material in Workshop 1 generally gave higher answers, with a smaller range (5-9), than those who only had access to replicated material in Workshop 2 (3-8). The mean scores (**TABLE 4**) calculated for both cohorts are very close, with the participants of Workshop 1 showing a mean value of 6.86, and those of Workshop 2 showing a mean value of 6.38. Regarding Visual Appearance, the scores given for Workshop 1 ranged from 4-10, with a mean value of 7.5, while for Workshop 2, the range was much larger, from 1-10, with a mean value of 5.43 (**TABLE 4**). For Tactile Feel, Workshop 1 provided scores from 3-10, with a mean of 7.63, while for Workshop 2, the scores ranged from 2-10, with a mean value calculated at 4.87 (**TABLE 4**). Finally, for Weight and Density, although there is the same range between the minimum and maximum figures, Workshop 1 had a range from 2-10, with a mean value of 6.13, and Workshop 2 had a range from 1-9 and a mean value calculated at 3.81 (**TABLE 4**).

Group B – Comparing all Three Workshops

TABLE 2 shows the results of the Mann-Whitney *U* tests run across all three workshops, comparing the scores between all individuals who had access to real skeletal material against all those who had access to replicated skeletal material. No statistical significance was noted within either the participants who had access to real skeletal material or those who had access to replicated material regarding Age Estimation. Lower minimum and maximum scores were given for the use of replicated skeletal material (3-8) than for the use of real material (5-9), with a lower mean score value determined for the replicated skeletal material (6.09) than for the real material (6.91).

TABLE 2 Comparing All Three Workshops. Workshop 1 – real skeletal material, Workshop 2 – replicated skeletal material, Workshop 3 – real and replicated skeletal material. *p<0.01.

Grouping	n	Min	Max	Mean	SD	Mann-Whitney *U* sig.
Sex Estimation using real skeletal material	37	5.00	10.00	7.81	1.30	0.72
Sex Estimation using replicated skeletal material	33	4.00	10.00	7.90	1.35	**0.01**
Age Estimation using real skeletal material	37	5.00	9.00	6.91	1.13	0.72
Age Estimation using replicated skeletal material	33	3.00	8.00	6.09	1.40	0.17
Visual Appearance using real skeletal material	37	4.00	10.00	7.91	1.40	**0.02**
Visual Appearance using replicated skeletal material	31	1.00	10.00	6.41	2.61	**0.03**
Tactile Feel using real skeletal material	37	3.00	10.00	7.97	1.46	0.12
Tactile Feel using replicated skeletal material	31	1.00	10.00	5.83	2.73	**0.03**
Weight and Density using real skeletal material	37	2.00	10.00	6.91	2.08	**0.00***
Weight and Density using replicated skeletal material	31	1.00	10.00	5.03	2.76	**0.00***

For both Sex Estimation and for Tactile Feel, statistical significances can be seen with the use of replicated skeletal material, but not with real material. For Sex Estimation, a *p*-value of 0.01 is noted for the use of replicated material, with a larger difference between the minimum and maximum scores given by participants (4-10) than for real skeletal material (5-10). The mean value is higher for scores relating to replicated skeletal material (7.90) than for those relating to real material (7.81). For Tactile Feel using replicated material, a *p*-value of 0.03 can be seen. Similar to Sex Estimation, for Tactile Feel there is a larger difference between the minimum and maximum scores provided by participants regarding replicated skeletal material (1-10) than for those relating

to real skeletal material (3-10). Additionally, the mean value is higher for students scoring real skeletal material (7.97) than for those scoring replicated skeletal material (5.83).

Statistical significances can be noticed for both real and replicated skeletal material regarding Visual Appearance, with *p*-values of 0.02 and 0.03 respectively. Again, a greater range of scores can be seen by respondents using replicated skeletal material (1-10) than by those using real material (4-10). The mean value for the use of real skeletal material is higher (7.91) than that for replicated material (6.41). Weight and Density also shows statistical significances for both real and replicated skeletal material, with both having *p*-values calculated at <0.00. Once more, a greater range of scores and lower minimum scores can be seen by respondents using replicated skeletal material (1-10) than by those using real material (2-10). Again, a higher mean value is shown for participants regarding real skeletal material (6.91) than for replicated skeletal material (5.03).

Group C – Comparing the Third workshop

TABLE 3 shows the results of the Mann-Whitney *U* tests run comparing the responses submitted by the participants in the third workshop, who had access to both real and replicated skeletal material. The only statistical significance noted within this set of tests is for Age Estimation, with a *p*-value of 0.02.

TABLE 3 Comparing Materials in the Third Workshop. Comparing the results of the real material against the replicated replicated skeletal material.

Grouping	n	Min	Max	Mean	SD	Mann-Whitney *U* sig.
Sex Estimation using real skeletal material	15	5.00	10.00	72.86	1.30	0.30
Sex Estimation using replicated skeletal material	15	4.00	10.00	7.26	1.35	
Age Estimation using real skeletal material	15	5.00	9.00	7.00	1.13	**0.02**
Age Estimation using replicated skeletal material	15	3.00	8.00	5.73	1.40	
Visual Appearance using real skeletal material	15	7.00	10.00	8.53	1.40	0.12
Visual Appearance using replicated skeletal material	15	3.00	10.00	7.46	2.61	
Tactile Feel using real skeletal material	15	7.00	10.00	8.46	1.46	0.06
Tactile Feel using replicated skeletal material	15	2.00	10.00	6.86	2.73	
Weight and Density using real skeletal material	15	5.00	10.00	8.06	2.08	0.07
Weight and Density using replicated skeletal material	15	1.00	10.00	6.33	2.76	

Participants gave higher minimum scores when using real skeletal material (5-10), than they did when assessing replicated skeletal material (3-8), with a higher mean value also calculated for real material (7.00) over replicated material (5.73). Similar can be said for the scores and mean values for Sex Estimation, with real

material scoring higher (5-10) and providing a higher mean value (7.86), than that from replicated material (4-10 and 7.26 respectively).

Regarding Visual Appearance, Tactile Feel and Weight and Density, all Likert scale answers had a smaller range when using real skeletal material (7-10, 7-10 and 5-10 respectively), unlike while using replicated skeletal material (3-10, 2-10 and 1-10 respectively). Again, the mean values were higher for the use of real skeletal material in all categories (Visual Appearance – 8.53, Tactile Feel – 8.46 and Weight and Density – 8.06), than for the use of replicated skeletal material (Visual Appearance – 7.46, Tactile Feel – 6.86 and Weight and Density – 6.33).

Discussion

Before reviewing the results of the analysis here, it is important to remember the wording of the questions, and their intention to determine the level of confidence of each participant. Regarding haptic sensation and visual texture: "How confident do you feel in your ability to identify real skeletal material based on visual texture/physical texture/weight and density (concerning the material you have had access to today)?" Participants were asked whether they believed the material that they were provided with would help them identify real skeletal material outside of the workshop. For the participants of Workshop 1 who had access to real skeletal material, this question asked if they would be able to use their experience with real skeletal material to potentially help identify the same type of material in the future. However, for the participants of Workshop 2, who only had access to replicated material, the question asked if they would be able to use their experience with replicated bone to help them identify real bone in the future, thus asking them if they could use one type of resource to identify something completely different. The participants of Workshop 3 potentially had an advantage as they were able to use both real and replicated material to determine their future abilities to identify real skeletal material, but this also put them in a better position to differentiate between the two types of resources.

Group A – Comparing the First and Second Workshops

For the first grouping no statistically significant differences were noted between the use of real and replicated skeletal material for creating a skeletal sex estimation. This could suggest that the participants of both workshops felt relatively confident in their ability to estimate the skeletal sex of the real or replicated skulls and os coxae they had access to. However, a lower range of participant scores was given for real skeletal material than for replicated, which could suggest that participants found it easier to create a skeletal sex profile using replicated skeletal material than real material. This could perhaps be attributed to handling. It is noted within osteological reference guides, such as Buikstra and Ubelaker (47) and White and Folkens (32), that manual interaction can assist in identifying specific traits and markers and siding specific bones. Real skeletal material, especially archaeological bones, can be delicate and brittle, meaning great care must be taken upon interaction. As casts are made from a more robust material than real bone, meaning they are less fragile and can be handled and manipulated more easily and for longer periods. The ability to feel specific reference points, such as the size and angle of the mastoid process and the sharpness of the orbital margins, could engage students more and help develop their understanding. This corresponds with the opinions of a participant in recent work conducted by Dawson-Hobbis (48), where one respondent commented that 'you never have to worry about breaking them' in reference to cast material.

Regarding age estimation, although the *p*-value of 0.05 is outside the range of statistical significance, it could be argued that it still highlights a notable variance between scores. The difference in minimum and maximum scores given for each workshop, and the slightly higher *p*-value obtained for the use of real skeletal material suggest that participants of the first workshop felt slightly more confident in completing an age estimation than those in the second workshop. By looking at participant comments, the overarching issue with the replicated material was the quality of the casting. Many participants of Workshop 2 added that they had difficulty with the second os coxa in the aging station (refer to the singular os coxa in **FIGURE 3**), stating that it was of poor quality and did not show sufficient features, such as the auricular surface, for any analysis. When choosing the material for the workshops, this os coxa was deliberately sought to demonstrate the varying levels of quality of the replicated material that is available, and thus the scope of what can be learned from certain pieces.

All three categories relating to haptic sensation and visual appearance recorded statistical significances within Group 1. In all instances, the minimum scores given by participants, and the subsequent mean values, are lower for the participants of Workshop 2 who only had access to replicated skeletal material. The overarching conclusion from these results is that participants felt significantly less confident in their abilities to identify real skeletal material after only having access to replicated material. Again, by looking at the participant comments, these statistics can be enhanced. Participant 41 (Workshop 2) stated "there was no difference between the types of bone" referring to the fact that it was not possible to differentiate between the compact cortical bone on the exterior and the porous trabecular bone on the interior at the fourth station (refer to the broken long bones in **FIGURE 3**). Again, the work of Dawson-Hobbis (48), reiterates this sentiment, that

anatomical details, weight and texture are lost in replications.

Group B – Comparing all Three Workshops

The results obtained from Group B – from combining and comparing the answers across all three workshops – show somewhat similar results to Group A results. Again, no statistical significance is noted regarding age estimation, but a higher mean value suggests that real skeletal material is more valuable for participant understanding and education than replicated material. A statistical significance was noted for sex estimation using replicated skeletal material which could suggest that participants felt less confident when attempting to create a skeletal sex profile from the replicated material. This could be likened to an anatomical study conducted by the Cordoba National University (49). Over a five-year period, the Cordoba study collected data from three student cohorts studying anatomy – one that only had timetabled access to real cadavers for dissection, a second that only had access to digital material, and a third that had access to both types of pedagogic resource. When analyzing the data collected from midterm and end of term exams, it was noted that the group who had access to both types of anatomical resource scored the highest marks. Having had access to both types of resource, students were deemed to have gained a better knowledge and understanding of anatomy.

However, looking further at the results for skeletal sex estimation, the mean value from the results of Group B was higher for replicated material than for real skeletal material, meaning that participants scored themselves higher overall for their confidence using replicated skeletal material. As with Group A, this could potentially be because of handling, with participants feeling more able to interact with the highly durable replicated material without fear of causing any damage. In which case, the reason for the statistical significance noted by the Mann-Whitney U test could possibly be seen in the mean values taken from both Workshop 1 and from the replicated skeletal material in Workshop 3 to create Group B (see **TABLE 4**).

TABLE 4 Comparison of means across all three workshops. Group A shows the results generated comparing the data between the participants of Workshop 1 (real skeletal material) and the participants of Workshop 2 (replicated skeletal material). Group B shows the results generated comparing the data between the participants of all three workshops (Workshop 1 – real skeletal material, Workshop 2 – replicated skeletal material, Workshop 3 – real and replicated skeletal material). Group C shows the results generated comparing the data between the Participants of Workshop 3 only (scores given by participants for real skeletal material and replicated skeletal material).

Grouping	Group A	Group A n	Group B	Group B n	Group C	Group C n
Sex Estimation using Real skeletal material	7.77	40	7.81	37	7.86	15
Sex Estimation using replicated skeletal material	8.44		7.90	33	7.26	
Age Estimation using real skeletal material	6.86		6.91	37	7.00	
Age Estimation using replicated skeletal material	6.38		6.09	33	5.73	
Visual Appearance using real skeletal material	7.50	38	7.91	37	8.53	
Visual Appearance using replicated skeletal material	5.43		6.41	31	7.46	
Tactile Feel using real skeletal material	7.63		7.97	37	8.46	
Tactile Feel using replicated skeletal material	4.87		5.83	31	6.86	
Weight and Density using real skeletal material	6.13		6.91	37	8.06	
Weight and Density using replicated skeletal material	3.81		5.03	31	6.33	

The mean score for Group A is 8.44, while for Group C the mean score is 7.26, marking a difference of 1.18. This in itself is noteworthy, and may suggest that participants had varying levels of confidence because of what materials they had access to as part of the workshop they attended. As the participants of Workshop 3 had access to both real and replicated skeletal material, they may have scored themselves differently to the participants of Workshop 1, who had no other type of resource present to relate to. In other words, the participants who had access to both types of resource could determine that there was a difference between the real and replicated material they had access to, and thus may have scored differently to participants who only had access to one type of resource.

Similar to the findings from Group A, statistical significances are noted across the three visual and tactile categories in Group B, apart from Tactile Feel using real skeletal material. When looking at the mean values, scores provided by participants were noticeably higher when working with real skeletal material: for Visual Appearance, the mean value was 1.50 higher for real material than for replicated; for Tactile Feel, the mean value was 2.14 higher for real material than for replicated; and for Weight and Density, the mean value was 1.88 higher for real material than for replicated. The *p*-values noted above, and these variances in mean values between real and replicated material, suggest that students gained a better understanding from the real material than from the replicated material. Further to the previously mentioned issues of bone type and texture, several respondents commented on the weight difference between the real and replicated material, with respondent 53 (Workshop 3), stating explicitly that the replicated bones were “heavier”.

Group C – Comparing the Third workshop

The results of Group C, taken from the third workshop, prove rather interesting. The only statistical significance noted as a result of the Mann-Whitney *U* tests is for age estimation. This tends to suggest that participants felt more confident in creating age-at-death profiles for the real skeletal material they had access to, rather than the replicated material. Although no other statistical significance was noted as part of the Kruskal-Wallis testing, differences can still be seen within the data. For each category, the mean value was higher for real skeletal material than for replicated (sex estimation – 0.6, age estimation – 1.27, visual appearance – 1.07, tactile feel 1.60, and weight and density – 1.73). These differences in mean values clearly show that participants felt more comfortable in their abilities based on their use of real skeletal material than on replicated. In the additional comments, several respondents appeared to include comparisons between the real and replicated material, with Respondent 46 stating that "the real ones [bones] had more detail and the spongy parts can be found, while casts fill the inside of the bone in". Participant 48 commented that "replicated skeletons generally are more heavy", suggesting that they had taken the time to hold and interact with both the real and replicated resources before arriving at that conclusion.

Broader discussion

Further to these points, there are more interesting trends which can be seen across the mean values. Regarding the real skeletal material used for sex estimation and for age estimation, the mean values are higher for Group C than Group A. This tends to suggest that the participants of Workshop 3 felt more confident in their abilities to identify real skeletal material than their counterparts in Workshop 1. Again, this could link back to the work of Biasutto and colleagues (49), whose study determined that students who had access to more than one type of anatomical learning resource gained a better understanding of the material. However, as a complete contrast to this, regarding the use of replicated skeletal material for the same categories, the mean values for participants in Group C are lower than those in Group A. This could suggest the opposite of what has been previously described; that those participants who only had access to replicated skeletal material (Workshop 2) felt much more confident in their abilities than those who had access to both real and replicated (Workshop 3). This is an extremely interesting pattern and could perhaps suggest that the participants of Workshop 3 were able to see a noticeable difference between the real and replicated material, thus providing lower scores for the replicated material.

As mentioned above, it seems that participants were interacting with the resources in such a way to notice the difference between the types of materials used. It could also imply that participants of Workshop 3 would be less likely to be able to identify real skeletal material in the future based off access to the replicated material alone in the workshop. However, the participants who solely had access to replicated skeletal material had no other physical references to act as a comparison, and so had to give their answers based on the casts and replicas which they had access to. It is worthy of note that participants 38, 39 and 40 (Workshop 2) did not answer all of the Likert scale questions, adding in that the question was not applicable because they only had access to casts. This could show that the participants did not feel they were able to gauge their abilities to identify real skeletal material based on the replicated material that they had access to in the workshop. Alternatively, there could have been a misunderstanding of what the question was asking,

Interestingly, for the three categories surrounding haptic sensation and visual appearance, the mean values are all higher for Group C than Group A, for both real and replicated skeletal material. It is understandable that lower mean values were obtained for the replicated material as replicating the texture of bone is extremely difficult in cast material, as can be seen in Figure 3 (and closer in Figure 1). By including both types of materials in Workshop 3, it seemed that participants were able to make more of the resources they had access to, and were able to actively compare between the real and replicated material to determine which was most useful for each part of their learning process.

Although numerous studies and bodies of work have been conducted on the best methods of creating age-at-death and skeletal sex estimations of individuals (such as 50,51;34, to list but a few), only limited literature has been published on the use of haptic sensation and visual appearance within osteology (i.e. 52,53,48). This is interesting, as there exists much work on the use of tactile learning and haptic sensation in the teaching of anatomy (54,55,56). Numerous studies have emphasized the enhanced learning benefits of the use of tactile learning through interaction with physical resources, in the form of human cadavers or plastinated specimens (57,58,59) and plastic or 3D printed models (60,61). Additionally, many studies have been undertaken relating to the need for specialists and surgeons to engage with physical resources to gain a better understanding of the sense of touch and pressure for dealing with living patients (62,63). Studies undertaken on the use of haptic sensation show correlation between physical interaction and memory (commonly referred to as haptic recognition) which suggest that the ability to touch and manipulate an object enhances learning ability and learning memory (64). In other words, being able to hold and physically interact with an object should allow for a greater understanding of

its shape, weight and density, key features, and surface texture. Further study on this may produce highly valuable insights into the learning potential of physical material in learning osteology and forensic anthropology.

Regarding the teaching of osteology, surface texture plays an important role in creating age-at-death profiles using the pelvic bones, whilst touching other skeletal markers can aid in skeletal sex estimation (32, 52). Additionally, students are also taught to look for signs of taphonomy and pathology, and are expected to be able to differentiate between the two. Once again, the disease state affects the bone and alters the surface texture. One reason that students may feel comfortable in identifying these aspects is because they have learnt from confirmed cases within a classroom environment, being given guidance by a lecturer who can specifically indicate what is present. Rather than students being taught to fully interact with human bone, getting a feel for the texture and looking at its composition, teaching might be more focused on how to identify specific aspects – such as the billowing and furrowing of the pubic symphysis needed for an age-at-death profile, and the specific traits of disease markers. These instances of course show that students are learning from the classes, and the approved syllabus, but perhaps they could learn more outside of this.

The validity of replicated skeletal material in teaching

A recent study undertaken by Carew and colleagues (65) used CT scanning to create digital versions of a series of archaeological bones before 3D printing them. The intention for this study was to determine whether the quality of the prints would be sufficient to be used in courts of law, rather than having to present real remains. The results showed near perfect digital replications, however the printed bones lacked fine texture and detail. It was also noted that the color was flat, as the color from the real counterparts cannot be replicated in a print. One specific print mentioned was the patella, which failed to replicate the eburnation present on the real bone (65). Another similar study using archaeological bones to create 3D prints held similar results (66). Specifically noted was that when replicating the auricular surface of one individual, the texture, porosity and surface margins were poorly represented. Once again, mainly details were lost from the samples, however, the billowing replicated on another pubic symphysis proved striking, and highly detailed. The authors of this research determined that this was because the individual was young and had pronounced features which were recreated well in the print (66). Linking in with this detail, a report penned by Baier and colleagues (67), determined that a 3D printed skull fragment was detailed enough to be used as evidence in a court of law. A section of a murder victim's skull was obtained for micro-CT examination and was subsequently 3D printed. The quality of the replication showed the details of the corresponding blunt force trauma injury and was able to be used as demonstrative evidence.

Studies of the accuracy of cast material are extremely sparse. The manufacturer Bone Clones® states explicitly that it only sells the highest quality, osteologically correct replicas. This could be attested to by the testimonials from customers, some of which are provided by professionals who intend to use them for teaching anthropology. Also, Respondent 27 (Workshop 2) of this study commented on the quality of the material, stating that 'Bone Clone material is very good and realistic'. However, as with 3D printing, it is impossible during the casting process to replicate the finer details, including the difference between the inner and outer layers of bone. Furthermore, good quality cannot be assumed of all the replicated material available for purchase online, perhaps meaning the margin for error with purchasing cast skeletal material is rather high and could be considered a financial risk for the purchasing institution. There are more details available on Bone Clones' testimonials available here: https://boneclones.com/page/testimonials.

The aforementioned studies show both successes and failures with replicating human bone through 3D printing. But in all cases, it was only the most prominent details which could be accurately replicated. This is the same with cast material. Any pronounced details can be replicated as part of the casting process, but the finer, more intricate details will be lost. Unfortunately, it is currently impossible to perfectly replicate the texture of human bone, meaning that certain important aspects might be lost. Although this may not always be the case; technology is ever advancing, and so it might be possible at some point to recreate human bone down to the finest detail.

This does not, however, mean that replicated skeletal material is not important or useful within higher education. When asked whether there was a difference between using real and replicated skeletal material, 92.85% of workshop attendees agreed that there was a difference. Further to this, when asked how participants believed skeletal anatomy should be taught in forensic science, all respondents selected that both real and replicated material should be used. Interestingly, many of the additional comments from participants appeared to link together, with similar opinions given by several participants. Participants from Workshop 1 leaned more into the use of both real and replicated skeletal material in higher education, with Respondent 4 commenting that 'replicated models lack details that are present on real bones' but then went on to say that 'replicated remains are useful when learning the anatomy'. Additionally, Respondent 20 stated that 'replicated is great for getting used to appearance such as the shapes and features', while Respondent 21 noted that 'using casts builds confidence

before using real remains'. These comments all prove interesting as the participants of Workshop 1 only had access to real skeletal material.

The main theme reflected in the comments of Workshop 2, however, was the low quality of the cast material, as noted by ten participants. Similarly, the participants in Workshop 3 appeared to focus more on the downsides of the casts, and their inability to recreate the fine details, although Participant 44 did state that 'replicated is good for learning the different elements'. Overall, the participants of this study leaned towards the idea of gaining familiarity of skeletal anatomy by using replicated skeletal material. Beginning by handling and manipulating replicated material can allow students to start building a basic knowledge of human skeletal anatomy, including the location of bones and articulations. However, for learning details which rely on visual and textual elements, students must move on to using real human skeletal material. In the ideal world, universities would be able to provide their students with both real and replicated skeletal material to enhance their study.

Possibilities for further research

It could be suggested that as the data gathered in this study did not focus on a formative, written approach, it is not as valid as the results of a formal assessment. However, the use of formative assessment is to not only aid the student, but also to assist the teacher in understanding the better methods of learning (68,69). In which case, the use of oral, in-class assessment could be as useful to the teacher as written, end-of-class tests. It could also be suggested that oral assessment allows for a deeper, and more comprehensive conversation between student and teacher, providing the teacher with a better insight into the student's knowledge and understanding of the topic at hand (70,71).

While formative, oral assessment during the workshop ensured that participants were fully engaging with the material and correctly identifying the skeletal markers required, subsequent student comments on the survey in regard to 'hesitation' and/or confidence' are at risk of becoming speculative in empirical assessment. As such, future research would benefit from both a quantitative and qualitative approach. Revisiting the thoughts of participants regarding their perceived confidence levels could be either confirmed or contradicted by the inclusion and comparison of formative, written assessment. If participants stated they felt more confident in identifying certain skeletal markers on replicated bone, for example, and then formative assessment found this to not be the case, it could once again question the usefulness of the materials being used to teach osteology. Additionally, it would be extremely useful to undertake this, or a similar study with a larger participant number. The possibility to work with a larger sample size would not only increase the data collected, but perhaps also enhance the reliability and accuracy of the results gained through statistical analysis.

Conclusions

The results and opinions generated by this study show an overwhelming need for the use of both real and replicated skeletal material to be used together for osteological education in forensic science. Many students agreed that replicated material was a useful introductory tool in learning the basics of skeletal anatomy, but the overarching response was that when learning the more detailed aspects of identification, mainly creating age-at-death profiles, having access to real skeletal material was far superior. Additionally, even with the most detailed casts, it is not yet possible to replicate the finest details of bone, including the highly porous trabecular interior, or differentiate between the inner and outer layers of bone. For cohorts at universities who only have access to replicated human remains, this could pose a significant problem which may potentially put students at a disadvantage if going out into real world of crime scene recovery.

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Ethical Approval

Before any research was undertaken, ethical approval was sought from Keele University. Project ID: 2024-0716815.

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