Le Moustier 1 Neandertal – The discovery of two new sets of casts, 3D reconstruction and comparison with original fossils

Mathilde Daumas a,⁎, 1, Tara Chapman a,⁎, 1, Stéphane Louryan a

a Laboratory of Anatomy, Biomechanics and Organogenesis (LABO), Faculty of Medicine, Université Libre de Bruxelles (ULB), Lennik Street 808, 1070 Brussels, Belgium
b Scientific Service Heritage, Royal Belgian Institute of Natural Sciences, 29 Rue Vautier, 1000, Brussels, Belgium
c Operational Direction Earth and History of Life, Royal Belgian Institute of Natural Sciences, 29 Rue Vautier, 1000, Brussels, Belgium

⁎ Corresponding author.
E-mail addresses: mathilde.daumas@ulb.be (M. Daumas), tchapman@naturalsciences.be (T. Chapman), Stephane.Louryan@ulb.be (S. Louryan).
1 Joint first authors.

https://doi.org/10.1016/j.daach.2021.e00204
Received 1 June 2021; Received in revised form 10 October 2021; Accepted 14 October 2021
Available online 23 October 2021
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1. Introduction

The adolescent Neandertal skeleton – Le Moustier 1 was most likely discovered in the layer H of the lower rock shelter or the Peyrony rock shelter at Le Moustier (commune of Le Moustier, Dordogne, Southwest of France) by the Swiss antiquary Otto Hauser in 1908 (Hauser, 1909; Maureille and Turq, 2005). The Le Moustier 1 bones were represented by at least a skull, several major long bones, and a series of postcranial bones. The Le Moustier 1 bones were not dated directly, however the layer where the specimens were theoretically discovered was dated to more than 42,000 and less than 46,000 years ago (Maureille and Turq, 2005; Mellars and Grün, 1991; Valladas et al., 1986). In 1910, Le Moustier 1 was sold to the Königliches Museum für Völkerkund in Berlin. The postcranial skeleton was subsequently destroyed in this Museum in a bombing raid at the end of the Second World War (Thompson and Nelson, 2005; Ullrich, 2005). Fragments of original bones were later recovered from the rubble of the building, although these fossils were badly damaged and suffered shrinkage and distortion as a result of the heat of the fire (Herrmann, 1977). The skull had previously been evacuated to a safe place outside of Berlin and was taken to the Soviet Union, but was later returned to Germany, where it is currently housed with the remains of the burnt fossilised fragments of the postcrania skeletal (Ullrich, 2005).

Le Moustier 1 is an adolescent, probably around 11–12 years of age (Thompson and Nelson, 2011; Rosas et al., 2017), which could help in the understanding of Neandertal ontogeny (Nelson and Thompson, 2005; Thompson and Nelson, 2011). Apart from Teshik-Tash whose dental age is 8–9 years old, (Gremiatsky, 1949), Le Moustier 1 is the only other juvenile Neandertal of this age category with cranial, dental and postcranial elements (Ullrich, 2005; Thompson and Nelson, 2011). There are relatively few infant and adolescent Neandertal skeletal remains that have been found and the majority are younger juveniles (Rosas et al., 2017). The recent discovery of the El Sidron J1 is a major historical find as the skeleton preserves cranial, dental and postcranial remains, although dental histology estimates the age of death of El Sidron J1 to be younger than Le Moustier 1 at only 7.7 years (Rosas...
Paleoanthropology has a long history in the use of casts of fossil bones and teeth (Monge and Mann, 2005). Before the skeleton was destroyed, a series of plaster casts were taken on the most complete bones of the skeleton (Thompson and Nelson, 2005). These casts have become important because the original fossils have either been destroyed, damaged or are no longer available (Herrmann, 1977; Thompson and Nelson, 2005). Of the known 11 postcranial casts which were taken, there are 5 which no longer exist as original fossils (left clavicle, first metatarsal, left and right fibulae, left patella).

Le Moustier 1 is not the only fossil hominin to go missing or be destroyed. The Homo erectus “Peking Man” fossils were also lost in 1941 although plaster casts were previously taken on the most important specimens (Janus, 1975). The Peking Man casts have a good level of detail and in most cases, the measurements on the cast are not significantly different from the published measurements on the originals (Mann and Monge, 1987). Casts taken from the original fossils preserve the external fossil shape and can sometimes be seen as a duplicate record of fossil bones, they are often used in place of original fossils for research and teaching and enable scientists to study and compare different fossil hominids around the world (Mann and Monge, 1987). However, relatively little attention has been paid to the moulding and casting techniques that produced casts (Monge and Mann, 2005). Early casts were generally made of plaster of Paris which are known to be dimensionally stable but preserve little detail apart from the general shape of the fossil. There are exceptions to this and moulds were sometimes made using keyed wedges of plaster of Paris which were built piece by piece around a fossil (Monge and Mann, 2005). As an example, the Chapelle-aux-Saints Neandertal skull was made according to this technique and was composed of hundreds of these wedges each reproducing a small section of the surface of the bone (Goodwin and Chaney, 1995; Mann and Monge, 1987; Monge and Mann, 2005). After the 1950s, silicone rubber, polyester and epoxy resin were more common materials to make replicas (Monge and Mann, 2005). More modern casting resins reproduce far greater levels of details although fossil casts produced using this material are not always dimensionally stable and can shrink, resulting in distorted dimensions of casts (Cook and Ward, 2008; Kondo et al., 2000; Monge and Mann, 2005).

Thompson and Nelson (2005) suggest that not only can casts be a viable alternative, but careful examination of casts can provide new details of Neandertal morphology. As Le Moustier 1 postcranial bones are mostly represented by casts, it is important to know how accurate the casts are in comparison to the originals and to examine how these casts were taken. Following Thompson and Nelson (2005), five different sets of the Le Moustier 1 casts have previously been identified and published. They are located in the Natural History Museum (London, United Kingdom), Horniman Museum (London, United Kingdom), Landesamt für Archäologie, (Halle, Germany - 2 sets) and the Department of Anatomy, University of Cape Town (South Africa). The same researchers state that the morphology of these casts is similar to the published morphology and measurements of the originals. In addition to the five published sets, there are also two unpublished sets: one at the Musée National de Préhistoire (Les Eyzies-de-Tayac, France) and one at the PACEA laboratory (University of Bordeaux, France). Two further new sets of casts of Le Moustier 1 can now be added to this list which are located in the Louis Deroubaix Museum (Université Libre de Bruxelles, Belgium) and the Royal Belgian Institute of Natural Sciences (Belgium). The first aim of this study was to examine the differences between the published measurements on the original bones (Klaatsch, 1905) and other casts (Thompson and Nelson, 2005) and then to compare them to measurements on the casts recently found in Belgium. The second aim was to examine the differences between the casts and their digitised models. The use of 3D models is frequent in forensic sciences and where access to original skeletal material (such as in mummies) or physical casts are unavailable (Chapman et al., 2020). Previous studies have found that there are negligible differences between measurements on the original objects and virtual measurements on the same digitised objects (Chapman et al., 2014; Lottering et al., 2014; Reynolds et al., 2017; Stull et al., 2014; Verhoff et al., 2008).

2. Materials and methods

2.1. Casts

As the original skull is still in existence, this study concentrates on the available 11 post-cranial casts of Le Moustier 1 (Fig. 1; Appendix). The 3D models of all bones from LDM are available to view at the following link: https://skfb.ly/o6CLR. This collection includes a cast of the skull and endocranium from LDM which was also discovered with the post-cranial bones. In the original Le Moustier 1 fossils there was an almost complete right humerus and the diaphysis of the left humerus, although to our knowledge, there are no casts of these bones. The radius and femur both have counterpart parts, although only the most complete bone was used to make casts.

This study adds two more available sets of casts of the Le Moustier 1 Neandertal. One set is from the Louis Deroubaix Museum (Museum of Anatomy and Embryology, LABO, Université Libre de Bruxelles, Brussels) subsequently designated as “LDM” casts. The other set is from the collections of the Royal Belgian Institute of Natural Sciences (Brussels), subsequently designated as “RBINS” casts. These two sets of casts are similar in size but differ in appearance. LDM casts are polychrome while RBINS casts are monochrome (Fig. 2; 3). Like Thompson and Nelson (2005) we assume that the colour difference indicates the portions which conform to the original bone and the reconstructed parts (Fig. 2; 3). The colour difference in the RBINS casts may also indicate the epiphyseal fusion stage. The epiphyses were missing on most of the long bones although they have been reconstructed (Figs. 1–3).

Previous authors have discussed how there is a difference in age estimates of Le Moustier 1’s dentition and postcrania (Nelson and Thompson, 1999, 2005; Thompson and Nelson, 2000). As none of the long bones had begun epiphyseal fusion this could indicate an age of 9–14 years old (Krogman and Iscan, 1986; Nelson and Thompson, 2005). The length of the long bones could indicate an age of 10.5 years using modern human standards (Thompson and Nelson, 2005), although Neandertals are well known for the shortness of the distal segment of their lower limbs in comparison to modern humans (Porter, 1999). Based on modern human references, dental age is corroborated by the third molars (Moorrees et al., 1963) and this relates to an immature specimen (between 15 and 17 in girls and 17–20 in boys). Using the same criteria, Nelson and Thompson, (2005) initially stated that Le Moustier 1 had a dental age of about 15.5 years old. However, Rossas et al. (2017) recently stated that in looking at the dental maturity of Le Moustier 1 in comparison to other Neandertals, the age of death may in fact be closer to 11.6–12.1 years of age. This is further confirmed by Thompson and Nelson (2011) who re-examined skeletal growth in Le Moustier 1 and stated that the age-at-death estimate was 11 years, stating that subadult Neandertals in middle childhood or adolescent age may be overaged using modern human dental criteria.

The age of the specimen is also related to sex. Applying established anthropological method for modern humans (Schueer and Black, 2000), the epiphyseal aspects of the femur, ulna, radius, fibula and metatarsal give an age of over 15 and under 18 if male and over 12 and under 15 if a female individual. Nevertheless, estimating sex is complex if not impossible for a juvenile before puberty (Majó et al., 1993; Schutkowski, 1993). However, based on general robustness and morphology, the literature (Klaatsch, 1909; Herrmann, 1977; Thompson and Nelson, 2005) identifies Le Moustier 1 as a young male. During the analysis of the available Le Moustier 1 casts, there were no arguments for or against this masculine diagnosis, which should therefore be taken with caution.
2.2. 3D models

All bones from LDM were processed by CT at the Radiology Department of the ULB Erasme Hospital (Siemens Sensations 64). Imaging settings were: image format = DICOM 3.0; image matrix = 512 x 512; slice thickness = 0.6 mm thickness and increment 0.4 mm, Voxel volume = 0.4 mm³. CT image stacks were imported into segmentation software (AMIRA®). On each bone, a semi-automated extraction of bone information was performed on the CT data and a 3D geometrical model was obtained. This procedure creates a faithful and accurate representation of bone, although included a high number of model mesh facets. Bone models need to remain useable to allow real-time simulation using standard computer graphics hardware, therefore all models were reduced to a manageable size and smoothed using MeshLab (http://www.meshlab.net/). Decimation was performed using Quadric Edge Collapse Decimation and models were reduced to a size of 20.192 triangles for the smallest bone (Metatarsal 1) up to 696.034 triangles for the largest bone (Femur).

2.3. Methods

Two anthropological researchers made manual measurements on the available casts (Fig. 1; Appendix) using callipers, an osteometric board, and tape for the circumference (Observer 1 and 2). Where possible, the same measurements were taken from the description of the originals (Klaatsch, 1909) and other casts (Thompson and Nelson, 2005) (Appendix). We also selected classical anthropometric measures (Appendix). A total of 69 postcranial measurements and 6 indexes were...
midpoint of the length measurements (Appendix). This was virtually done in lhpFusionBox by creating a landmark at the midpoint of the maximum length measurement. It was not possible to take the circumference of the digital bones in lhpFusionBox. In addition to this, the maximum or minimum midshaft size was not possible to do in 3D as it requires placing landmarks around the midshaft.

Klaatsch (1909) published length measurements on the original fossils and the casts from LDM and RBINS were compared with these measurements (Appendix). In addition to this, the measurements taken by Thompson and Nelson (2005) on the casts of the Natural History Museum of London were similarly repeated on the physical bones of RBINS and LDM by two observers and also on the digitised version of the casts of LDM (Appendix). A Wilcoxon Signed-Rank test was performed to assess the reliability of the measurements on the casts (LDM and RBINS) compared to the original fossils and to previously published measurements on other casts, assess inter-cast and inter-observer error, as well as assess the reliability of measurements on the digitised model in comparison to the original fossils and the physical casts.

To visualize the agreement obtained between observer and data source a Bland-Altman plot was created (the x-axis represents the mean value of the two measurements and the y-axis represents the difference between the two measurements). This method reveals systematic biases, checks the independence of the error from the value of the measurement, and identifies if a measure cannot be considered to be reliable. Since indexes are not direct measurements, they were removed from the Bland-Altman plot.

Statistical analysis was performed with the 8 measurements made on the original fossil by Klaatsch (1909) (mainly length measurements) and with the 59 measurements and indexes provided by Thompson and Nelson (2005) (Appendix). The LDM and RBINS casts were described by 79 physical direct measurements and indexes, whilst a total of 54 measurements were taken on the 3D models (Appendix).

3. Results

Measurements were taken both virtually and physically on all available postcranial bones from both LDM and RBINS (Figs. 1–3; Appendix). All measurements performed by Klaatsch (1909), Thompson and Nelson (2005), as well as measurements taken in the present study are available in the supplementary material (Appendix). For an extensive description of the cast morphology, see Thompson and Nelson (2005).

3.1. Bones and measurement description

3.1.1. Left rib 2

Klaatsch (1909) does not mention ribs in his original publication. However, Herrmann (1977) mentions the excavation of fragments of the left and right rib 2 and the left rib 2. Only casts of the left rib 2 fragment are preserved in both LDM and RBINS. It mainly consists of the posterior angle (angulus costae) whilst both the neck (collum costae) and head (caput costae) are missing. Only the maximum measurement was taken, as defined by Thompson and Nelson (2005).

3.1.2. Left clavicle

The original left clavicle has completely disappeared (Herrmann, 1977) although a cast of a large part of the left clavicle is available from both LDM and RBINS. The medial end (extremitas sternalis, after costoclavicular ligament insertion) and lateral end (extremitas acromialis, after conoid tubercle) are missing. There are no reported measurements of this bone from Klaatsch (1909), although the published measurements of Thompson and Nelson (2005) were repeated by two observers and also taken digitally (Appendix). As le Moustier 1 is an immature specimen, measurements linked to the conoid tubercle (tuberculum conoïdeum) were difficult to take on the plaster cast and it was not possible to identify this tubercle in the 3D model.
3.1.3. Right scapula

Only a tiny portion of the small fragment of the scapula found during the excavation survived the fire (Herrmann, 1977). The cortical surface was reported as severely degraded, revealing the internal structure (Thompson and Nelson, 2005). Klaatsch (1909) did not list any measurements although Thompson and Nelson (2005) performed several measurements on the glenoid cavity (cavitas glenoidalis) even though they reported this surface as lost, as well as the infra-glenoid tubercle. They also took the axillo-spinal angle, although no details exist on how they took this measurement. It was very difficult to distinguish the supra and infra glenoid edges, which made it difficult to gauge the glenoid cavity length and breadth on the cast, and this was even more apparent on the 3D model. We also believe this may be the cast of a left scapula and not a right scapula.

3.1.4. Right radius

Originally, the right radius and the shaft of the left radius were recovered. Of these two fossils, only a small portion of the distal end of the right radius survived (Thompson and Nelson, 2005). The original right radius was missing most of the epiphyses (which were most likely not yet fused) but they have been reconstructed on both the casts from LDM and RBINS. The radial tuberosity (tuberositas radii) is well defined on all casts. There is not a precise definition of articular length in Thompson and Nelson (2005), therefore we have considered this measurement to be the physiological length (Appendix).

3.1.5. Right ulna

The original excavation uncovered an almost complete right ulna with missing epiphyses as well as the diaphysis of a left ulna. According to Herrmann (1977), 78 mm of the distal third of the right ulna survived the fire of the museum, although it has not been found since and a heavily damaged 5 cm fragment of the left ulna is all that is left (Thompson and Nelson, 2005). The cast of the right ulna with reconstructed proximal epiphyses was found in both LDM and RBINS. The maximum length (ULX) was impossible to take according to Martin’s exact definition (Appendix; Martin and Saller, 1957). The trochlear notch (incisura troclearis) faces anteriorly but the radial notch (incisura radialis) was barely visible.

3.1.6. Left femur

In the original fossils, both the left and right femorae were excavated and both were damaged by the fire. Only portions of the diaphysis remain: two fragments for the left and one for the right, with additional losses due to chemical and histological analysis (Thompson and Nelson, 2005). Fortunately, a cast was made of the left femur before its destruction. The lesser trochanter (trochanter minor), greater trochanter (trochanter major), one-third of the femoral head and most of the distal epiphyses are reconstructed. Apart from the condyle diameter from Klaatsch (1909) and longitudinal head length, distal articular breadth and meric index from Thompson and Nelson (2005), where no precise definition exists, all other measurements were taken (Appendix).

3.1.7. Left patella

Both the left and right patella were excavated and have since disappeared. A cast was taken of the left patella only. The cast is difficult to interpret because we do not know if an incomplete reconstruction was done or if the bone presented an anatomical variation (patella bipartita). The exact surface of the medial and lateral facet (facies articulares) were difficult to decipher, as the edges were not well developed, and therefore it was difficult to measure in 3D (Appendix).

3.1.8. Left tibia

The original excavation found both tibiae, however, a cast was only taken on the left tibia. This cast includes the reconstruction of both the distal and proximal epiphyses (Fig. 2). Only a severely damaged fragment of the left tibia proximal end has survived (Thompson and Nelson, 2005). Some measurements detailed in Thompson and Nelson (2005), could not be carried out during the present study as we were uncertain how those measurements were taken. The physiological length is likely to be the condyle-astragalar length (Appendix). We also found that it was not possible to take the AP diameter, ML diameter and circumference at the nutrient foramen and cnemic index as the surface of both of the casts did not allow us to visualize the precise position of the nutrient foramen.

3.1.9. Left and right fibula

Hauser (1909) mentioned only one fibula, although both the left and right fibulae were supposed to have been excavated and both have now completely disappeared, presumed destroyed. However, two counterpart casts exist, the proximal part of a left fibula and the distal part of a right one (Appendix). The proximal epiphyses of the left fibula seem unfused. We have approximated the midshaft minimum diameter with the midshaft AP diameter in 3D and the midshaft maximum diameter with the midshaft ML diameter in 3D (Appendix).

3.1.10. Left first metatarsal

Hauser (1909) mentioned several “small fragments of foot bones” during the excavation but the original bone (or bones) has disappeared. Only a cast of the left first metatarsal (MTT1) remains.

3.2. Statistics

There was no significant difference in the Wilcoxon Signed-Ranks test when looking at the differences between the original fossil measurements (Klaatsch, 1909) and measurements on the casts from the Natural History Museum (Thompson and Nelson, 2005) (p = 0.4469). Similarly, no difference was found in measurements between the original fossils (Klaatsch, 1909) and casts from LDM between either observer (Observer 1, p = 0.6224 and Observer 2, p = 0.7998) as well as the RBINS casts (p = 0.7998). A Wilcoxon Signed-Rank test also showed that there was no statistical difference between measurements of Klaatsch (1909) and measurements on the digitised models of the casts from LDM (p = 0.6406). Although we kept it in our statistical analysis, one measurement seemed problematic: Klaatsch (1909) provides an ulna maximum length (ULX) of 210 mm while all the other measurements performed in our study fell between 190.9 and 192 mm for both casts and observers (Appendix). Thompson and Nelson (2005) also obtained a similar result to us for this measurement (Appendix).

There was no statistical difference between the previously published measurements of the casts from Thompson and Nelson (2005) and the casts from LDM (Observer 1, p = 0.2087 and Observer 2, p = 0.1078) or the RBINS casts (p = 0.2743). The Wilcoxon Signed-Ranks test also showed no statistical difference between the previously published measurements from Thompson and Nelson (2005) and the measurements on the digitised models of the casts from LDM (p = 0.4377).

Both observers independently measured the same LDM casts. The Wilcoxon Signed-Ranks test showed no statistical difference (p = 0.793) between them. Once the indexes were removed, the Bland-Altman plot did not show any growth in the difference between measurements as the average size of the measurement increased (Fig. 4A). Differences were randomly distributed between positive and negative values (mean difference of –0.1 mm). The upper and lower agreement levels were –2.2 to +2 mm regardless of the measurement (length, diameter or perimeter). The two outliers were the clavicle midshaft circumference (CMD) and the femoral subtrochanteric transversal diameter (FSTD).

One observer independently measured both the LDM and RBINS casts. There was no statistical difference between all 79 measurements (including indexes) from the casts from LDM and RBINS (p = 0.3066). The Bland-Altman plot also did not show any bias (with or without the index, Fig. 4B). The mean difference is 0.05 mm, with upper and lower agreement levels at –0.87 to +0.99 mm regardless of the measurement. We did however find 9 outliers: clavicle midshaft circumference...
Fig. 4. A. Bland-Altman plot depicting the differences in osteometric variables collected from the same LDM casts by different observers (LDM_obs1- LDM_obs2). B. Bland-Altman plot depicting the differences in osteometric variables collected by the same observer from the LDM and RBINS casts (LDM_obs2-RBINS_obs2). C. Bland-Altman plot depicting the differences in osteometric variables collected by the same observer from the physical and digitised LDM casts (LDM3D_obs1- LDM_obs1). D. Bland-Altman plot depicting the differences in osteometric variables collected by one observer from the physical LDM casts and another observer from the 3D models of the same LDM casts (LDM3D_obs1- LDM_obs2).
(CMC), radial distal minimum circumference (RDCS), ulna maximum length (ULX), ulna physiological length (UPL), ulna midshaft circumference (UMC), AP diameter of the lateral condyle (FDLC), patella medial facet breadth (PMFB), tibia maximum length (TLX) and tibia physiological length (TLP). The most important differences were found for ULP, FDLC and TLP. Despite these 9 outliers, all fell within a difference of less than 1.4 mm, except the TLP which had a difference of 2 mm. From these analyses, we can conclude that there were no differences between LDM and RBINS casts.

The Wilcoxon Signed-Ranks test showed no statistical difference (p = 0.05192) between the measurements performed on the physical and digitised LDM casts by the same observer (Appendix). On the other hand, there was a statistical difference when we compared measurements taken on the physical cast by one observer and measurements taken on the same digitised cast by another observer (p = 0.03714). This means that we cannot conclude that there is no difference inter-observer and inter-methods.

The Bland-Altman plot did not show any growth in the difference between measurements as the average size of the measurement increased (Fig. 4C and D). For intra-observer inter-method comparison (Fig. 4C), the mean difference was -0.14 mm, the lower and upper agreement levels were -2.5 to +2.2 mm. The 3 outliers were the tibial maximum length (without spine) (TLX), the femoral subtrochanteric transversal diameter (FSTD) and the femoral AP diameter of the medial condyle (FDMC) from the smallest to the largest error. For inter-observer inter-method comparison (Fig. 4D), the mean difference was -0.26 mm and the lower and upper agreement levels were -2.24 to +1.72 mm. The 2 outliers were the FDMC and the midshaft maximum diameter of the left fibula (FiMDX). Whereas FDMC was 57 mm when measured on both casts by both observers, the 3D measurement was 60.31 mm, therefore we conclude that this measurement seems problematic virtually.

4. Discussion

When we consider the classical measurements, the Le Moustier 1 casts recently discovered at LDM and RBINS showed no statistical differences from the original fossils described by Klaatsch (1909) or the casts described by Thompson and Nelson (2005). This demonstrates that these casts seem to be a relatively faithful reproduction of the original bones. Given that the original remains were either damaged or destroyed at the end of the Second World War, these plaster casts can be seen as a useful teaching aid and scientific replica of the original bones. As juvenile remains, they are also an important addition to the Neandertal fossil collection (Ullrich, 2005; Thompson and Nelson, 2005). Before this discovery, there were five different published sets of Le Moustier 1 casts. Thompson and Nelson (2005) only published measurements for the casts housed at the Natural History Museum, although they found that the measurements were similar for all casts.

The detailed description of how the measurement was obtained was not always available in Klaatsch (1909) or Thompson and Nelson (2005). Therefore, there were some measurements of the fossils or casts that we were unable to replicate because of a lack of definition. Where possible, we assumed which measures had been carried out. For example, the “femoral length” was the most wide-ranging variable in the literature, varying from 376 to 382 mm (Klaatsch, 1909; Thompson and Nelson, 2005). However, “femoral length” may correspond to 3 different measurements (maximum length “FLX”, length in position “FLP” or trochlear length “FLT”, Appendix). Moreover, in our specific case, length measurements can only be seen as estimates for the long bones in particular, as they seem to be in a large part reconstructed (Figs. 1–3). The difference in ulna maximum length between the original fossil (Klaatsch 1909) and the casts (both Thompson and Nelson (2005) and our study) is probably due to the presence or absence of the distal epiphyses on the reconstruction. This could also be the case for the maximum length of the radius to a lesser extent.

Whilst no statistical differences were found when performing the Wilcoxon Signed-Ranks tests between the physical LDM and RBINS casts themselves there were a few outliers from the Bland-Altman plots (Fig. 4). When examining the difference between two different observers on the same cast, it was found that there only two outliers: the clavicle midshaft circumference (CMD) and the femoral subtrochanteric transversal diameter (FSTD) (Fig. 4A). Both differences in these measurements may have been due to the way different observers took the measurements. All other measurements were found to be reliable.

When examining the differences between measurements on the LDM and RBINS casts taken from the same observer we found that there were 9 outliers (Fig. 4B). Whilst some of the outliers were circumferences which could be attributed to human error, others were maximum lengths where human error could be less relevant since osteometric tables were used. Osteometric tables requires users to place the bones in a specific way and the same observer would most likely measure the bones in the same manner. The maximum lengths were among the greatest values and this could also explain a greater variability. As all differences between the casts are less than 1 mm, we believe that this is a normal error of measurement, although we cannot exclude some subtle differences in the two different sets of casts.

Like many other casts produced in the 19th century, relatively little attention was paid to the moulding and casting techniques that produced the models. The casts at RBINS were made with gypsum by Dr F. Kranz Rheinisches Mineralien – Kontor and were most likely made after the first world war as the company acquired the rights to produce them in 1913. There is little knowledge on how the plaster casts of Le Moustier 1 at LDM were produced or who took the casts and how the reconstructions of the original bones were done. However, we know that the casts were taken at least before the Second World War. As the Moustier 1 is a juvenile, the majority of the epiphyses are missing and have been reconstructed in both sets of casts. It is not possible to tell which part was reconstructed and which was the original bone from the RBINS casts, while this seems to be possible with the casts from LDM (Fig. 2; 3). There is a lack of detail on both sets of the casts although similar to other early plaster casts, they seem to be dimensionally stable. Muscle attachments and markings are always less clearly defined in juveniles than in adult specimens and unfortunately muscle markings on the Le Moustier 1 casts at both LDM and RBINS are entirely lacking. This also made some measurements difficult to take, such as those associated with the nutrient foramen.

This study showed that there were no statistical differences between measurements taken on the casts from LDM and RBINS when compared to those taken on the original fossils published by Klaatsch (1909) and on the other available casts (Thompson and Nelson, 2005). There was a statistical difference between the measurements of the physical casts of LDM by one observer and the measurements on the same virtual cast by the other observer. However, no other differences were found between the 3D models and previously published data and original fossils or when the same observer performed both the physical and digitised measurements on the same casts. The difference is most likely due to the orientation of the bone in the virtual software. It seems logical that the more you compile the differences (methods, observers), the more biases you have and the more you reduce the reliability of the measurements. However, the majority of intra-observer and inter-observer inter-methods measurements fell within the upper and lower agreement levels in the Bland-Altman plots, which was approximately 2 mm (Fig. 4A). As with Stull et al. (2014), we assume that an error range of 2 mm is tolerable for anthropological assessment, and may come from various origins: scanning parameters, 3D reconstruction parameters, measurement errors, observer experience, etc. This result therefore agrees with other studies where measurements on the same physical and digitised objects were mainly found to be not statistically different (Chapman et al., 2014; Lottering et al., 2014; Reynolds et al., 2017; Stull et al., 2014; Verhoff et al., 2008).

When examining the differences between measurements taken on the virtual model and the physical model demonstrated by the Bland-
Altman plot we found that there were three outliers, the tibial maximum length (without spine) (TLX), the femoral subtrochanteric transversal diameter (FSTD) and the femoral AP diameter of the medial condyle (FDMC). The FSTD was already an outlier in a previous Bland-Altman plot (Fig. 4A) demonstrating that this is a difficult measurement to take. The difference is therefore likely to be from the way that the measurement was taken.

Although the statistics were not significant, it is important to note that the midshaft measurements were smaller in the digitised models (Appendix). We reconstructed the 3D models for a second time to see if there was a problem with the models, although we found that the error was not in model reconstruction as the same pattern was found. The models were created with the same protocol as detailed in Chapman et al. (2014) where measurements of the physical and digitised bones were similar. The problem was found to be related to how the virtual measurements were taken. Some measurements were difficult or impossible in a virtual setting (Appendix) and therefore were not easily replicated.

Lee et al. (2017) have previously highlighted that the distance between two vertical planes (i.e. in a physical osteometric board) is not the same as maximum femur length (FLX, Appendix) measured using Computed Tomography (CT). The length measurements were not statistically different from the digitised and original and physical models but it may be useful in the future to perform these types of anthropological measurements using planes and this may also assist with mid-shaft measurements. Reynolds et al. (2017) further highlight the benefit of a plane application in that planes can be automatically aligned to the most extreme points of the bone quickly and with ease, which reduces observer bias present in manual selections. The lhFusionBox software allows you to place anatomical landmarks (and then distances are measured between landmarks) although it does not currently allow users to measure between two planes or two parallel points. It is also sometimes difficult to understand scale in a 3D model as you frequently change the scale on the screen by zooming in and out (although this does not affect measurements and the simulation of the sliding calliper does help the researcher see measurements in real-time, similar to a digital calliper). Moreover, the maximum or minimum midshaft are difficult measurements to take in a virtual setting as it requires placing landmarks all around the midshaft and measuring distances from two isolated points rather than two planes or parallel points. Conversely, the physiological length in the tibia is a difficult manual measure to take with callipers due to the contours and curvature of the proximal and distal surface and it was found that it was easier to take this measurement in the 3D model. This was expected as the curvatures are considered with the 3D anatomical landmarks, whereas a calliper doesn’t take the curvatures into account. Similarly, the measurement of some surfaces (the glenoid cavity of the scapula and the medial and lateral facet of the patella) were difficult to gauge due to not knowing where the edges were because of the lack of details in the casts.

There are difficulties in using cast material as a source of metric data. However, due to the disappearance of the original bones, the possession of original casts can be seen as an asset, despite their imperfection. Le Moustier 1 is a sub-adult Neandertal and therefore can also be used as a comparative analysis. Antón (2005) argues that the gross morphology of casts allows preliminary research to be undertaken on the casts before the originals can be studied (if available) and that widely distributed casts of fossils can influence ideas about the morphology of a particular species, due to the fact that they are more widely studied.

High accuracy was noted intra-observer, between the observers and between both new casts. Even if all the measurements were not perfectly reliable, most of them fell within the acceptable range of variation of 2 mm. The CT scans of the LDM casts enabled the creation of 3D models of Le Moustier 1 that are now freely available. These digitised models can be used as an acceptable resource to analyse the shape and global morphology of Le Moustier 1, an immature Neandertal specimen. However, consideration needs to be given to the lack of details present in these plaster casts. The way measurements are taken in 3D also needs to be improved so that measurements on digitised specimens can be taken in the same way as traditional measurements on physical bones.

**Declaration of competing interest**

None.

**Data statement**

3D STL copies of all casts of Le Moustier 1 recently found in the Louis Deroubaix museum, Université Libre de Bruxelles (ULB), Brussels, Belgium (including the skull and endocranium) are available from the following link: https://skfb.ly/o6CLR. All bones are available on request from the authors.

**CRediT authorship contribution statement**

Mathilde Daumas: Validation, Formal analysis, Investigation, Writing – original draft. Tara Chapman: Methodology, Validation, Investigation, Writing – original draft. Stéphane Louryan: Conceptualization, Supervision, Project administration, Funding acquisition.

**Acknowledgements**

Many thanks to Mrs. Charlotte Van Humbeeck from the department of medical imaging, Hôpital Académique Erasme, Université Libre de Bruxelles for scanning the fossil casts. Thank you to Dr Patrick Semal, Director of Scientific Service Heritage at the Royal Belgian Institute of Natural Sciences (RBINS) for allowing us to measure the Le Moustier casts housed at RBINS. Thank you also to Dr F. Kranz Rheinisches Mineralien – Konter for providing details of the dates that the casts held at RBINS were moulded. We would further like to thank the contribution of reviewers who helped to improve the original manuscript. LhpFusionBox is available for non-commercial purposes as part of a research agreement with ULB (contact sintjans@ulb.ac.be). The lhF software was not finished.
originally developed as part of the LHDL project using the MAF application framework developed by the BioComputing Competence Center, Bologna, Italy (http://www.openmaf.org).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2021.e00204.

References


