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Virtual reconstruction of cranial remains: the *H. Heidelbergensis*, Kabwe 1 fossil

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Abbreviated title:

Virtual reconstruction of Kabwe 1

Introduction

Archaeological human skeletal remains are typically recovered during excavations of funerary contexts. Such remains provide considerable paleobiological information about past populations (Katzenberg & Saunders, 2011), however they are frequently fragmented due to taphonomical factors, which limits research (Stodder, 2007; Waldron, 1987). Similarly, fossil specimens (which are the focus of this manuscript) are usually fragmented, distorted and invaded by sedimentary matrix, thus limiting subsequent research on morphological evolution and disparity (Arbour & Brown, 2014; Neeser et al., 2009). This has led researchers to physically reconstruct fragmented hominin crania, such as OH 5 (Leakey, 1959; Tobias, 1967) or Zhoukoudian (Tattersall & Sawyer, 1996; Weidenreich, 1937). However, physical reconstruction is heavily based on anatomical expertise and involves multiple assumptions, making it a subjective process with limited reproducibility (Benazzi et al., 2009c). Moreover, the Le Moustier Neanderthal cranium is an unfortunate example showing that physical reconstruction using original specimens may be detrimental to the preservation of fossils (G. W. Weber & Bookstein, 2011).

Ready access to computing power and new specialist software have enabled limitations to reconstructing specimens using computer based approaches to be overcome. Virtual reconstruction is now a common procedure that has been applied not only to hominin fossils (Amano et al., 2015; Benazzi et al., 2011a; Benazzi et al., 2014; Grine et al., 2010; Gunz et al., 2009; Kalvin et al., 1995; Kranioti et al., 2011; Neubauer et al., 2004; Ponce De León & Zollikofer, 1999; Watson et al., 2011; C. P. E. Zollikofer et al., 2005; C. P. E. Zollikofer et al., 1995), but also in the context of biological and forensic anthropology (Benazzi et al., 2009a; Benazzi et al., 2009b; Benazzi et al., 2009c) and cranial surgery (Benazzi et al., 2011b; Benazzi & Senck, 2011). Such reconstructions are commonly based on CT scans, which provide detailed imaging of bone and capture external and internal anatomy. Once completed, such reconstructions can be used in several ways, to make a physical model using 3D printing, submitted to morphometric analyses or used in studies of biomechanics including finite element analysis (FEA) (Strait et al., 2005).

CT scan based reconstructions begin with segmentation, during which the relevant structures are identified and labelled within the scanned volume based on differences in density, and thus on grey level Hounsfield Units (Gerhard W. Weber, 2015; G. W. Weber & Bookstein, 2011). Segmentation choices depend on the intended further use of the model. If used only for visualisation purposes in which detailed internal anatomical reconstruction is of no concern, single thresholds (set values of Hounsfield Units) that segment most of the structure can be used. Such thresholds may be set manually or calculated using a variety of approaches (Coleman & Colbert, 2007; Spoor et al., 1993), but will either exclude bones that are too thin to be selected or overestimate bone thickness. Thus, if detailed anatomy is important, complex approaches that combine global, regional and manual thresholding are necessary (G. W. Weber & Bookstein, 2011). In such cases one may set a global threshold and subsequently apply thresholds to specific anatomical regions that were not selected by previous thresholding. Finally, manual segmentation is usually necessary for fine details that were not picked up by the previous approaches.

Once the segmentation process is finished, reconstruction of missing anatomical regions begins. This process usually combines imaging software (e.g. Avizo/Amira) and geometric morphometrics (GM) to approximately restore the original geometry of an incomplete/distorted specimen (Gerhard W. Weber, 2015; G. W. Weber & Bookstein, 2011). In specimens that preserve one side intact the most straightforward approach is to use bilateral symmetry (Gunz et al., 2009) to reconstruct the damaged side. In such cases it is possible to reflect the preserved regions onto the incomplete side and use them to replace the missing areas (Gunz et al., 2009). However, no skeletal structures are completely symmetric and crania present different magnitudes of asymmetry (Quinto-Sánchez et al., 2015). Thus, reflected regions will not perfectly fit the remaining preserved anatomy. To overcome this mismatch, and account for asymmetry, it is possible to warp the reflected structure onto the remaining preserved anatomy (Gunz et al., 2009). This warping uses a mathematical function based on shared landmarks to deform the landmarks and regions between landmarks from one specimen (usually referred to as the reference) into the space of a second specimen (usually referred to as the target) such that landmarks coincide and the material between them is smoothly interpolated between reference and target forms. The most commonly used function in virtual anthropology, for good statistical and mathematical reasons (minimisation of deformation), is the thin plate spline (TPS; Bookstein, 1989).

Even though this is a desirable approach, fossils often lack preserved structures on both sides or along the midline, thus precluding reflection. In these cases reference based reconstruction (Gunz et al., 2004; Gunz et al., 2009) should be used. The choice of reference specimen should be considered carefully so as to not bias the reconstruction and it has been suggested that references should be species specific (Gunz et al., 2009; Senck et al., 2015; C. P. Zollikofer & Ponce de León, 2005). Such reconstructions may be statistical or geometric (Gunz et al., 2004; Gunz et al., 2009; Neeser et al., 2009). Statistical reconstruction uses patterns of covariance in a given sample to predict the locations of missing landmarks via multivariate regression (Gunz et al., 2009; Neeser et al., 2009). Geometric reconstruction uses the TPS function to estimate the positions of missing landmarks based on known ones (Gunz et al., 2004; Gunz et al., 2009). The latter has the advantage of requiring only one specimen, which may be a particular individual or a mean specimen calculated from a given sample using GM (Gunz et al., 2009) but it omits information on intra specific covariations. However, Senck and Coquerelle (2015) show that using mean specimens yields good results when reconstructing large portions of incomplete specimens. Furthermore, where sample sizes are limited to one or a few specimens, as with fossils, TPS based warping can be applied, whereas statistical approaches cannot.

Reconstruction choices impact the final result, hence they have to be considered carefully (Gunz et al., 2009; Senck et al., 2015). One option is to exclude fragmentary or damaged specimens from analysis, however when dealing with fossil remains, the number of specimens is commonly very low and their exclusion may be detrimental to the study. In fact, in a study that examines the impact of different reconstruction approaches and of exclusion of incomplete specimens on morphological analysis, Arbour and Brown (2014) show that it is better to estimate missing landmarks, and thus reconstruct missing anatomy, than to exclude incomplete specimens. This is because the inclusion of incomplete specimens with estimated missing landmarks may better reflect the morphological variance of a sample than excluding incomplete specimens, especially when the available sample is small, as is often the case with fossils.

In this manuscript the steps are presented that were used to make a full reconstruction of Kabwe 1, a middle Pleistocene hominin cranium (dating from150 - 250 thousand years before present) that has been classified as *Homo heidelbergensis* (Stringer, 2012). Despite missing some parts of the right side of the cranium and other localised bony structures (e.g., ethmoidal cells, orbital region of the maxilla and ethmoid) it is one of the best preserved crania in the hominin fossil record (Schwartz & Tattersall, 2003). The reconstruction is intended for use as the basis of FEA studies in which the functional performance of this specimen will be compared to that of other hominins. Biomechanical studies using FEA are increasingly common (e.g. Benazzi et al., 2015; Ledogar et al., 2016; Smith et al., 2015; Strait et al., 2007; Strait et al., 2009; Strait et al., 2010; Wroe et al., 2010) but for the results to be meaningful detailed and accurate anatomical restoration is necessary. Thus, in this reconstruction, internal and external anatomy was carefully restored. For morphometric studies of external morphology, less effort is required to reconstruct internal anatomical detail. Although the methodology for reconstruction is described in the context of a fossil, it is equally applicable to modern human skeletal remains.

Materials and Methods

The cranium of Kabwe 1 is remarkably well preserved but is missing some anatomy due to taphonomic and pathological processes (Schwartz & Tattersall, 2003). Missing areas include a large portion of the right side of the cranial vault and base (parts of the right temporal, right parietal and occipital), right zygomatic, maxilla, teeth and small portions of the orbital cavities (Figure 1). Reconstruction was based on a CT scan (courtesy of Robert Kruszynski, Natural History Museum, London) performed with a Siemens Somatom Plus 4 CT scanner, with voxel size of 0.47 x 0.47 x 0.50 mm and 140 kVp, and was divided in four main phases (Figure 2). In the first phase, the existing anatomy was segmented from the scanned volume. This was followed by reconstruction of the left side of the vault, which was then used to reconstruct the large missing region on the right side of the cranium. Lastly, all remaining missing features were reconstructed.

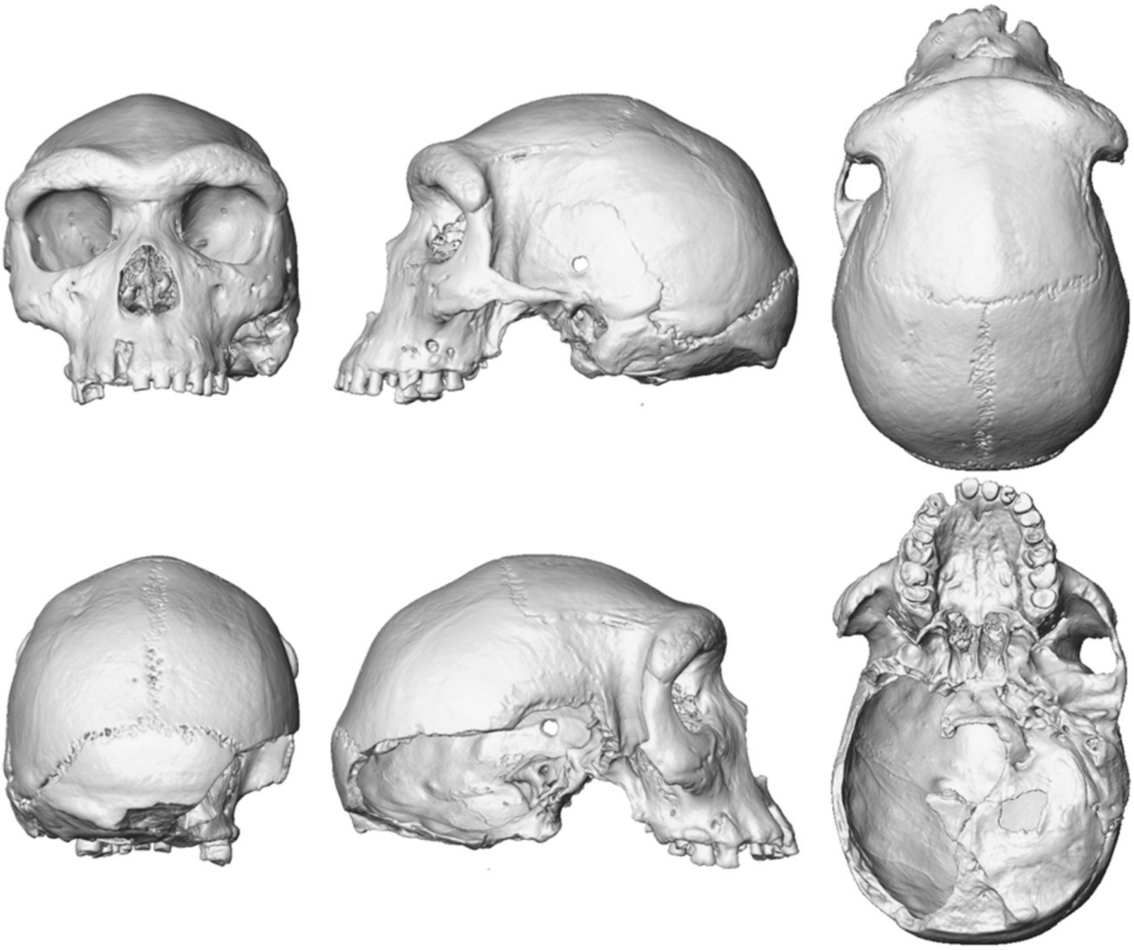

Figure 1: Standardized views showing missing bony structures of the cranium of Kabwe 1. Note that, despite some missing portions, the cranium is extremely well preserved and presents no distortion.

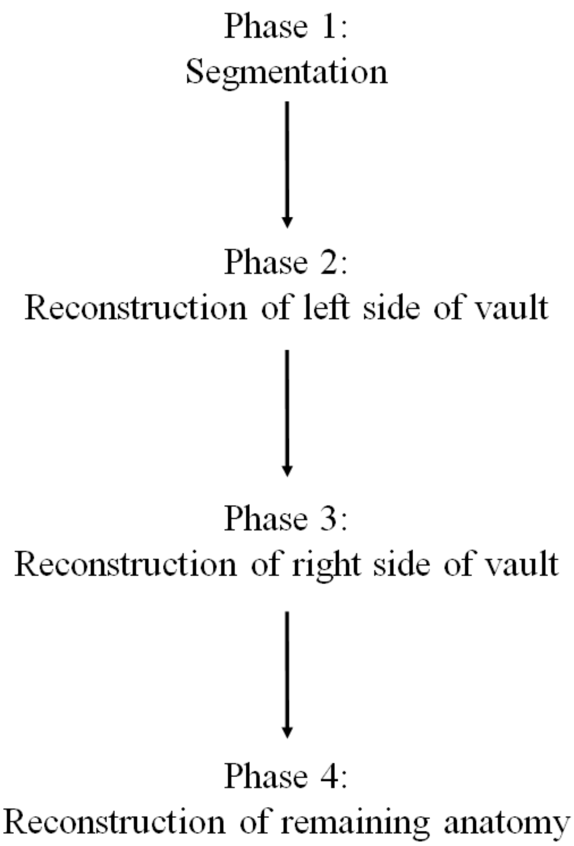

Figure 2: Workflow of the reconstruction of Kabwe 1.

Segmentation was performed in Avizo 7.0 and used a combination of approaches. First, the half maximum height value (HMHV; Spoor et al., 1993) was calculated and applied to the whole volume for threshold segmentation. This inevitably excluded thin bones, requiring the use of regional thresholds as a second step, applied to specific anatomical regions, such as parts of the ethmoid bone. This allowed semi-automated segmentation of more, but not all, of the bony anatomy without overestimating bone thickness. Thus, manual segmentation was required for fine details of thin bones. Teeth were segmented separately, which required calculation of specific thresholds to avoid overestimating their dimensions. Last, it was necessary to remove sedimentary matrix that had invaded the cranium. This required a manual approach due to overlap of grey values between matrix and bone.

Once segmentation was complete, the left half of the cranium was mirrored to reconstruct the missing large right portion of the cranium that includes parts of the parietal, temporal, occipital and zygomatic bone. Because of asymmetry, the reflected region did not fit the remaining preserved anatomy perfectly. Thus it was necessary to warp it to the preserved structures. TPS based warping was performed using Avizo 7.0 using 20 existing landmarks (bregma, nasion, rhinion, anterior nasal spine, zygomaxillare, lambda, jugale, infra-orbital foramen, prosthion, orale, incisive foramen, staphylion, hormion, foramen lacerum, inferiormost point of lateral pterygoid plate, inferiormost point of medial pterygoid plate, pterygoid fossa, basion, opistion, staphanion) and resulted in an almost perfect fit between reconstructed and preserved anatomy that required minimal manual editing. After warping, only the reconstructed regions were preserved and the remaining reflected hemi-cranium was discarded. The alveolar process of the right hemi-maxilla was also restored by reflecting the preserved contra-lateral region. Regions that presented gaps (orbital surfaces of the maxilla and ethmoid, periapical regions of the maxilla, left temporal bone, occipital bone, nasal cavity walls, ethmoid bone and vomer) were reconstructed using a combination of manual editing and the software Geomagic 2011 to interpolate between existing bone edges. The missing portion of the occipital bone, affecting the superior nuchal line, was reconstructed using the occipital of a modern human cranium, manually editing it to adjust its morphology. Editing was performed in Geomagic 2011. Teeth were restored by reflecting existing antimeres. When this was not possible portions of teeth from a modern human were used to reconstruct incomplete teeth.

Figure 3: Standardized views showing the original (dark grey) and the reconstructed (translucent grey) crania of Kabwe 1.

Results and Discussion

The reconstruction of Kabwe 1 allowed restoration of missing anatomical regions (Figures 3 and 4) and, in our particular application, creation of a model for further use in FEA. While it was carried out as objectively as possible, any reconstruction, physical or virtual, requires assumptions and a certain degree of subjectivity (Gunz et al., 2009). Thus other reconstructions will likely yield different results, but disparities are likely very small in most regions because segmentation was mainly based on global and regional half maximum height values and restoration was highly constrained by existing structures which provided good local information on general contours and proportions. Additionally the use of objective GM based approaches reduced guesswork.

Figure 4: Standardized views showing the reconstructed cranium of Kabwe 1.

The segmentation process relied mainly on global and regional thresholds that were selected using HMHVs. This provides a generally objective approach but depends on the sites at which the values are measured and it does not segment the whole cranium without further manual intervention if bone thickness is not to be overestimated. Thus, while this process is generally reproducible, minor differences relative to other possible segmentations are to be expected due to differences in sites where grey levels are measured and subjective decisions during manual segmentation.

Reconstruction of the large missing portion on the right side of the vault and base used the reflected left side, which was then warped based on the TPS function to account for asymmetry. This procedure is expected to yield good results and to outperform statistical reconstruction based on multivariate regression because it used the same individual and the reflected region was warped to the existing anatomy. The TPS warping used classical landmarks and no sliding semi-landmarks. While these potentially improve warping, only minor differences are to be expected because the reference is individual specific (reflected left hemi-cranium), TPS warping used several landmarks in the vicinity of the restored region and the reflected warped portion fitted the target region almost perfectly.

While it would be preferable to use species specific homologous structures to restore teeth and the occipital we did not have access to other *Homo heidelbergensis* specimens. As such, a modern human was used and its morphology was manually edited after warping to account for morphological differences in the nuchal line region of the occipital. Furthermore, reconstruction was only performed as far as the midline and the contra-lateral side was reconstructed using the reflection/TPS based warping procedure. Visual assessment of the smoothness of the reconstruction provides confidence that the original morphology is likely closely approximated and that the results of using other approaches may differ only slightly.

The use of mesh editing software such as Geomagic to fill small gaps (in the occipital bone, alveolar region of the maxilla, orbital cavities and temporal bone), is very efficient and visual assessment shows smooth reconstructions. The region in which reconstruction was most subjective was in defining the cells of the ethmoid bone, and this was performed manually. An alternative approach would have been to use the ethmoid bone of a modern human (to the best of our knowledge no other closely related fossil hominin has this bone fully preserved), warping its ethmoid to replace the existing incomplete bone. While this would have been more objective, the bone forming the ethmoid sinus is extremely thin and has limited load bearing significance during biting (Ross, 2001). Moreover, because it is so thin, warping would likely have required further manual editing. Thus, while results would have been different they would probably have had minor, if any, impact on subsequent work based on this reconstruction.

As mentioned above, any reconstruction is subjective (Gunz et al., 2009). Thus, several studies have assessed the impact of reconstruction approaches and compared the impact of using TPS based estimation of missing landmarks vs. multivariate regression vs. mean specimen (Arbour & Brown, 2014; Gunz et al., 2009; Neeser et al., 2009), reference specimen selection (Gunz et al., 2009; Neeser et al., 2009), sample size of reference sample (Neeser et al., 2009) and number of missing landmarks (Arbour & Brown, 2014). Based on these studies we are confident that the present reconstruction reasonably approximates the original morphology.

Nonetheless, it is feasible, and in many circumstances desirable, to carry out studies assessing the impact of different reconstruction approaches on the eventual virtual model and on results of subsequent analyses using the model. Thus, morphometric comparison of different variants of the same reconstruction can inform with regard to the nature and magnitude of any differences in size and shape. The significance of such differences in relation to the results of comparative morphometric studies can be assessed by incorporating different versions of the reconstruction, assessing within reconstruction (specimen) variation relative to among specimen variation. Similarly, the impact of morphological reconstruction choices on predicted stresses and strains from FEA can be assessed through sensitivity analyses that compare results among variant reconstructions (Fitton et al., 2015; Parr et al., 2013; Parr et al., 2012; Toro-Ibacache & O'Higgins, 2016).

Virtual reconstruction of damaged skeletal material from CT scans has opened up new possibilities in virtual anthropology and archaeology. We are at the beginning of this virtual revolution, although even at this stage the power of these approaches is evident, with rapidly increasing rates of publication of studies employing them to gain new insights into old material. As technologies for imaging and segmentation, improve and as workers add new tools to the virtual anthropology toolkit we can anticipate continued growth of interest and an exciting future for the field in which hitherto inaccessible remains may yield important and occasionally surprising new morphological information.

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