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

2

3 Ricardo Miguel Godinho and Paul O'Higgins

4

5 Abbreviated title:

6 Virtual reconstruction of Kabwe 1

7

## 8 Introduction

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

24 Ready access to computing power and new specialist software have enabled limitations  
25 to reconstructing specimens using computer based approaches to be overcome. Virtual  
26 reconstruction is now a common procedure that has been applied not only to hominin  
27 fossils (Amano et al., 2015; Benazzi et al., 2011a; Benazzi et al., 2014; Grine et al.,  
28 2010; Gunz et al., 2009; Kalvin et al., 1995; Kranioti et al., 2011; Neubauer et al., 2004;  
29 Ponce De León & Zollikofer, 1999; Watson et al., 2011; C. P. E. Zollikofer et al., 2005;  
30 C. P. E. Zollikofer et al., 1995), but also in the context of biological and forensic  
31 anthropology (Benazzi et al., 2009a; Benazzi et al., 2009b; Benazzi et al., 2009c) and  
32 cranial surgery (Benazzi et al., 2011b; Benazzi & Senck, 2011). Such reconstructions

33 are commonly based on CT scans, which provide detailed imaging of bone and capture  
34 external and internal anatomy. Once completed, such reconstructions can be used in  
35 several ways, to make a physical model using 3D printing, submitted to morphometric  
36 analyses or used in studies of biomechanics including finite element analysis (FEA)  
37 (Strait et al., 2005).

38 CT scan based reconstructions begin with segmentation, during which the relevant  
39 structures are identified and labelled within the scanned volume based on differences in  
40 density, and thus on grey level Hounsfield Units (Gerhard W. Weber, 2015; G. W.  
41 Weber & Bookstein, 2011). Segmentation choices depend on the intended further use of  
42 the model. If used only for visualisation purposes in which detailed internal anatomical  
43 reconstruction is of no concern, single thresholds (set values of Hounsfield Units) that  
44 segment most of the structure can be used. Such thresholds may be set manually or  
45 calculated using a variety of approaches (Coleman & Colbert, 2007; Spoor et al., 1993),  
46 but will either exclude bones that are too thin to be selected or overestimate bone  
47 thickness. Thus, if detailed anatomy is important, complex approaches that combine  
48 global, regional and manual thresholding are necessary (G. W. Weber & Bookstein,  
49 2011). In such cases one may set a global threshold and subsequently apply thresholds  
50 to specific anatomical regions that were not selected by previous thresholding. Finally,  
51 manual segmentation is usually necessary for fine details that were not picked up by the  
52 previous approaches.

53 Once the segmentation process is finished, reconstruction of missing anatomical regions  
54 begins. This process usually combines imaging software (e.g. Avizo/Amira) and  
55 geometric morphometrics (GM) to approximately restore the original geometry of an  
56 incomplete/distorted specimen (Gerhard W. Weber, 2015; G. W. Weber & Bookstein,  
57 2011). In specimens that preserve one side intact the most straightforward approach is

58 to use bilateral symmetry (Gunz et al., 2009) to reconstruct the damaged side. In such  
59 cases it is possible to reflect the preserved regions onto the incomplete side and use  
60 them to replace the missing areas (Gunz et al., 2009). However, no skeletal structures  
61 are completely symmetric and crania present different magnitudes of asymmetry  
62 (Quinto-Sánchez et al., 2015). Thus, reflected regions will not perfectly fit the  
63 remaining preserved anatomy. To overcome this mismatch, and account for asymmetry,  
64 it is possible to warp the reflected structure onto the remaining preserved anatomy  
65 (Gunz et al., 2009). This warping uses a mathematical function based on shared  
66 landmarks to deform the landmarks and regions between landmarks from one specimen  
67 (usually referred to as the reference) into the space of a second specimen (usually  
68 referred to as the target) such that landmarks coincide and the material between them is  
69 smoothly interpolated between reference and target forms. The most commonly used  
70 function in virtual anthropology, for good statistical and mathematical reasons  
71 (minimisation of deformation), is the thin plate spline (TPS; Bookstein, 1989).

72 Even though this is a desirable approach, fossils often lack preserved structures on both  
73 sides or along the midline, thus precluding reflection. In these cases reference based  
74 reconstruction (Gunz et al., 2004; Gunz et al., 2009) should be used. The choice of  
75 reference specimen should be considered carefully so as to not bias the reconstruction  
76 and it has been suggested that references should be species specific (Gunz et al., 2009;  
77 Senck et al., 2015; C. P. Zollikofer & Ponce de León, 2005). Such reconstructions may  
78 be statistical or geometric (Gunz et al., 2004; Gunz et al., 2009; Neeser et al., 2009).  
79 Statistical reconstruction uses patterns of covariance in a given sample to predict the  
80 locations of missing landmarks via multivariate regression (Gunz et al., 2009; Neeser et  
81 al., 2009). Geometric reconstruction uses the TPS function to estimate the positions of  
82 missing landmarks based on known ones (Gunz et al., 2004; Gunz et al., 2009). The

83 latter has the advantage of requiring only one specimen, which may be a particular  
84 individual or a mean specimen calculated from a given sample using GM (Gunz et al.,  
85 2009) but it omits information on intra specific covariations. However, Senck and  
86 Coquerelle (2015) show that using mean specimens yields good results when  
87 reconstructing large portions of incomplete specimens. Furthermore, where sample sizes  
88 are limited to one or a few specimens, as with fossils, TPS based warping can be  
89 applied, whereas statistical approaches cannot.

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

101 In this manuscript the steps are presented that were used to make a full reconstruction of  
102 Kabwe 1, a middle Pleistocene hominin cranium (dating from 150 - 250 thousand years  
103 before present) that has been classified as *Homo heidelbergensis* (Stringer, 2012).  
104 Despite missing some parts of the right side of the cranium and other localised bony  
105 structures (e.g., ethmoidal cells, orbital region of the maxilla and ethmoid) it is one of  
106 the best preserved crania in the hominin fossil record (Schwartz & Tattersall, 2003).  
107 The reconstruction is intended for use as the basis of FEA studies in which the

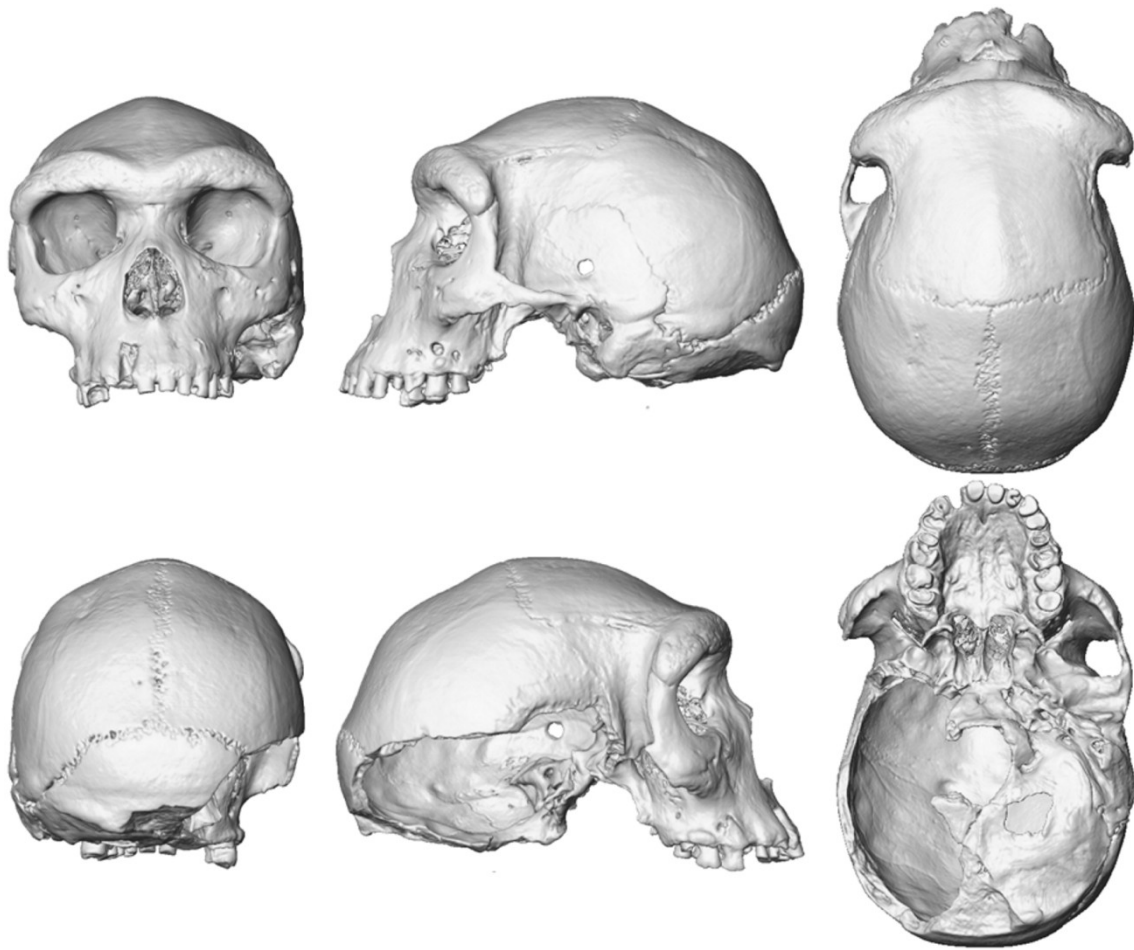
108 functional performance of this specimen will be compared to that of other hominins.  
109 Biomechanical studies using FEA are increasingly common (e.g. Benazzi et al., 2015;  
110 Ledogar et al., 2016; Smith et al., 2015; Strait et al., 2007; Strait et al., 2009; Strait et  
111 al., 2010; Wroe et al., 2010) but for the results to be meaningful detailed and accurate  
112 anatomical restoration is necessary. Thus, in this reconstruction, internal and external  
113 anatomy was carefully restored. For morphometric studies of external morphology, less  
114 effort is required to reconstruct internal anatomical detail. Although the methodology  
115 for reconstruction is described in the context of a fossil, it is equally applicable to  
116 modern human skeletal remains.

117

## 118 Materials and Methods

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

130



131

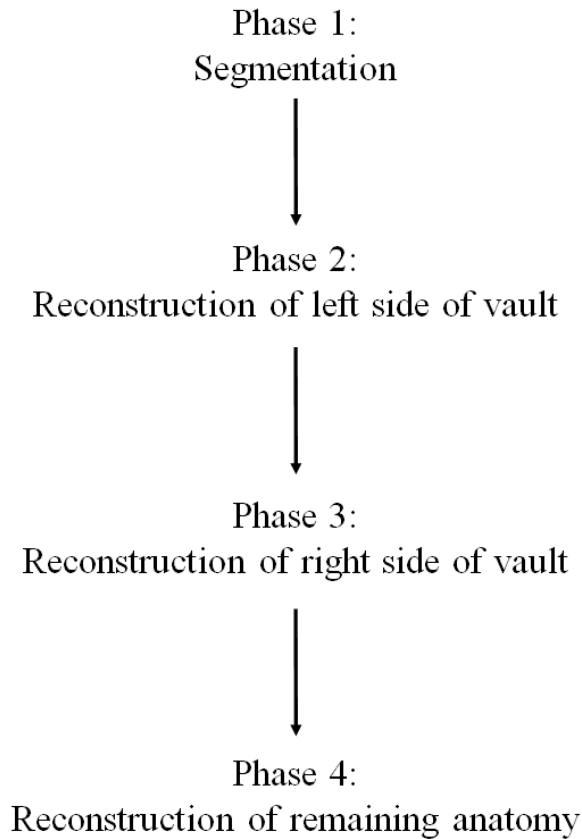
132 Figure 1: Standardized views showing missing bony structures of the cranium of Kabwe

133 1. Note that, despite some missing portions, the cranium is extremely well preserved

134 and presents no distortion.

135





136

137 Figure 2: Workflow of the reconstruction of Kabwe 1.

138

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

148 the cranium. This required a manual approach due to overlap of grey values between  
149 matrix and bone.

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

172



173

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

176

## 177 Results and Discussion

178 The reconstruction of Kabwe 1 allowed restoration of missing anatomical regions  
179 (Figures 3 and 4) and, in our particular application, creation of a model for further use in  
180 FEA. While it was carried out as objectively as possible, any reconstruction, physical or  
181 virtual, requires assumptions and a certain degree of subjectivity (Gunz et al., 2009).  
182 Thus other reconstructions will likely yield different results, but disparities are likely  
183 very small in most regions because segmentation was mainly based on global and

184 regional half maximum height values and restoration was highly constrained by existing  
185 structures which provided good local information on general contours and proportions.  
186 Additionally the use of objective GM based approaches reduced guesswork.

187



188

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

190

191 The segmentation process relied mainly on global and regional thresholds that were  
192 selected using HMHV. This provides a generally objective approach but depends on  
193 the sites at which the values are measured and it does not segment the whole cranium  
194 without further manual intervention if bone thickness is not to be overestimated. Thus,

195 while this process is generally reproducible, minor differences relative to other possible  
196 segmentations are to be expected due to differences in sites where grey levels are  
197 measured and subjective decisions during manual segmentation.

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

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

217 The use of mesh editing software such as Geomagic to fill small gaps (in the occipital  
218 bone, alveolar region of the maxilla, orbital cavities and temporal bone), is very

219 efficient and visual assessment shows smooth reconstructions. The region in which  
220 reconstruction was most subjective was in defining the cells of the ethmoid bone, and  
221 this was performed manually. An alternative approach would have been to use the  
222 ethmoid bone of a modern human (to the best of our knowledge no other closely related  
223 fossil hominin has this bone fully preserved), warping its ethmoid to replace the existing  
224 incomplete bone. While this would have been more objective, the bone forming the  
225 ethmoid sinus is extremely thin and has limited load bearing significance during biting  
226 (Ross, 2001). Moreover, because it is so thin, warping would likely have required  
227 further manual editing. Thus, while results would have been different they would  
228 probably have had minor, if any, impact on subsequent work based on this  
229 reconstruction.

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

238 Nonetheless, it is feasible, and in many circumstances desirable, to carry out studies  
239 assessing the impact of different reconstruction approaches on the eventual virtual  
240 model and on results of subsequent analyses using the model. Thus, morphometric  
241 comparison of different variants of the same reconstruction can inform with regard to  
242 the nature and magnitude of any differences in size and shape. The significance of such  
243 differences in relation to the results of comparative morphometric studies can be

244 assessed by incorporating different versions of the reconstruction, assessing within  
245 reconstruction (specimen) variation relative to among specimen variation. Similarly, the  
246 impact of morphological reconstruction choices on predicted stresses and strains from  
247 FEA can be assessed through sensitivity analyses that compare results among variant  
248 reconstructions (Fitton et al., 2015; Parr et al., 2013; Parr et al., 2012; Toro-Ibacache &  
249 O'Higgins, 2016).

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

259

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265

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