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Effective approaches to three-dimensional digital reconstruction of fragmented human skeletal remains using laser surface scanning

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ABSTRACT

The preservation and reconstruction of anthropological and archaeological remains has been given considerable attention in recent years, particularly within the fields of forensic science and palaeoanthropology. However, few studies have tapped the potential of using 3D technology to reconstruct, remodel and recontour remains and artefacts for the purpose of human identification. The aim of this study was to use 3D technology for the reconstruction and remodelling of fragmented and missing elements of skeletal remains. This project presents the application of three dimensional (3D) modalities to two different simulated forensic case scenarios where an attempt was made to remodel the missing element of the human cranium and reconstruction of fragmented replicated human mandible was performed. The accuracy of the reconstructed model was affirmed based on the anatomical features and digital analysis and methods for use in forensic practice are recommended.

1. Introduction

In forensic anthropology and medicine, the superimposition of the cranial remains onto an individual's photograph and/or facial reconstruction is a frequent method for the identification of missing individuals [1]. However, this greatly depends upon the integrity of the cranial components [1]. Thus, the reconstruction of lost and distorted bone presents a challenge [2]. Forensic anthropology particularly deals with skeletal remains. Various physical anthropological techniques have been presented for identification from skeletal remains by means of age and sex estimation, dental comparison, skull photo-superimposition, etc. [3–6]. Similarly, facial approximation helps to recognize an individual by plastic reconstruction using manual or computerized methods [7,8]. All these techniques can only be performed on the intact cranium for the accurate results. Moreover, challenges might have been perceived by the forensic experts while assessing injuries in skeletal remains due to fragmented presentation. Such situations must be addressed in order to avoid impedance in accurate interpretation of the evidence.

The current decade has seen the rapid development of new methods of imaging, visualizing and analysing human skeletal remains [9]. Traditional crime scene and forensic reconstruction and documentation methods are now giving way to three-dimensional (3D) imaging [10–13]. Methods include X-ray computed tomography (including micro-CT) [14,15], laser scanning [15,16], structured-light scanning [16], and 3D photogrammetry [9,17]. A number of researchers have emphasized the clear advantages to 3D digitization over other recording techniques i.e. examination of fragile and otherwise inaccessible material, the production of affordable, high-quality replicas for display, teaching, and research, increased accuracy and enhanced data sharing [7–14,17,18]. The use of surface scanning in forensic anthropology and medicine has been well established [19], in contexts such as the analysis of burned remains [20], replication of anthropological specimens for curation and illustration [20], recording taphonomic changes [21], evaluating trauma [1,22], determining bullet pathways [23], and presenting evidence in court [24–26].

3D printing is an advanced technology that creates a model similar to the original object [9]. One of the earliest medical

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modelling applications involved the 3D printing of anatomical study models [27]. 3D printing is currently being used in the biomedical sciences and the methods regarding the reconstruction of scanned images/objects are continually researched [9,17,19]. Recently, studies have demonstrated the importance of 3D printing for remodelling of skeletal remains as demonstrative evidence in court [24–26,28,29]. Indeed, many countries i.e. United Kingdom [25,26], Germany [24], Poland [30] now accept 3D prints in court. Carew et al. in their research into the accuracy of 3D modelling and 3D printing in anthropological reconstruction using six commercially available printers concluded the prints produced using selective laser sintering were most consistently accurate [31].

Traditional approaches to the reconstruction of fragmented remains involve the application of adhesives to the bones themselves, or the addition of modelling clay [18,32–34]. In theory, incomplete and fragmented osseous remains can be restored by reproducing the external integrity of bony segment and reconstructing the fragmented remains. Additive manufacturing techniques can be adopted by forensic experts, anthropologists, radiographers, and pathologists to create the physical profile of the skeletal remain in question [8,35,36]. Recent work has shown the potential of this on fragmented bone using a physical fit analysis framework, however there are contexts where fragments of bone are missing and in these cases, physical fit analysis is not possible [20].

The aim of this technical note was to examine two approaches to managing fragmentation of crania in contexts of human identification and provide recommendations for practice. The first focused on fixing missing skeletal features, while the second approach focused on reconstructing broken bones.

2. Case 1: Reconstruction of missing bony features

2.1. Fragmented skeletal remains acquisition

After obtaining an approval from the Ethics Committee of the institution, a human cranium of known age and sex was obtained from the skeletal archives of Laboratory of Forensic Odontology, Gujarat Forensic Sciences University, Gujarat, India for the scanning procedure. It presented with bilaterally missing zygomatic process (Fig. 1 A). A second human cranium of similar age and sex but with intact zygomatic processes was also obtained from the same archive (Fig. 1 B) for scanning purpose.

2.2. Scanning process

Digital scans were made using NextEngine® 3D Laser Scanner (NextEngine Inc., Santa Monica, California) with an accuracy of ±100 μm for digital restoration. The set-up specifications [37] are 100-240VAC built-in auto-switching power supply, source of twin arrays of four class 1M 10mW solid state lasers with custom optics 650 nm λ, twin 5.0 Megapixel CMOS image sensors, Optically synchronous 7-color surface capture for precision-locked geometry correlation photo surface, spatially diverse white light illuminators with tri-phosphor, wide colour gamut photo lighting, 5.1" × 3.8" (Macro) and 13.5" × 10.1" (Wide) field size, target surface capture density up to 268K points/in (Macro), 29K points/in (Wide), texture density 500 DPI on target surface, dimensional accuracy ± 0.005", acquisition speed 50,000 processed points/sec throughput (2 min per scan of each facet). Scans were output as '. *stl*' files. (Fig. 2).

2.3. Digital 3D reconstruction

For the digital reconstruction, Geomagic Studio 13® (Geomagic Inc., 3D systems, North Carolina, USA) software was used for the precise reproduction of surfaces. The workflow involved a number of commands and steps (Fig. 3) which are summarized as follows:

A. Define objects: The scanned data of the cranium with intact zygomatic process (reference) was defined as *'fixed object'* and the scanned data of the cranium with missing zygomatic process (test) was defined as *'floating object'* in the software.
B. Manual alignment: Both data (*fixed object & floating object)* were aligned in *'XYZ co-ordinates'*; by using *'manual alignment'* tool from '*n-point alignment*' selection under '*alignment tab'*. Three points were selected at homologous locations on both the crania in three planes (X, Y and Z). In this case, the first point was selected on frontal bone, second point on occipital bone and third point at the base of the crania. Thus, aligning data of both the crania in similar position.
C. Global registration: To ensure accurate overlap of data of both the crania and appearance of smooth surface, fine-tuning of the alignment between the two objects was achieved by '*global registration'* under the *'alignment tab'*. In this case it was resulted in average deviation of 0.986 mm where as standard deviation of 0.794 mm.

A B

Fig. 1. A: Lateral and basal view of cranium with bilaterally missing zygomatic process; B: Lateral and basal view of cranium with intact zygomatic process.

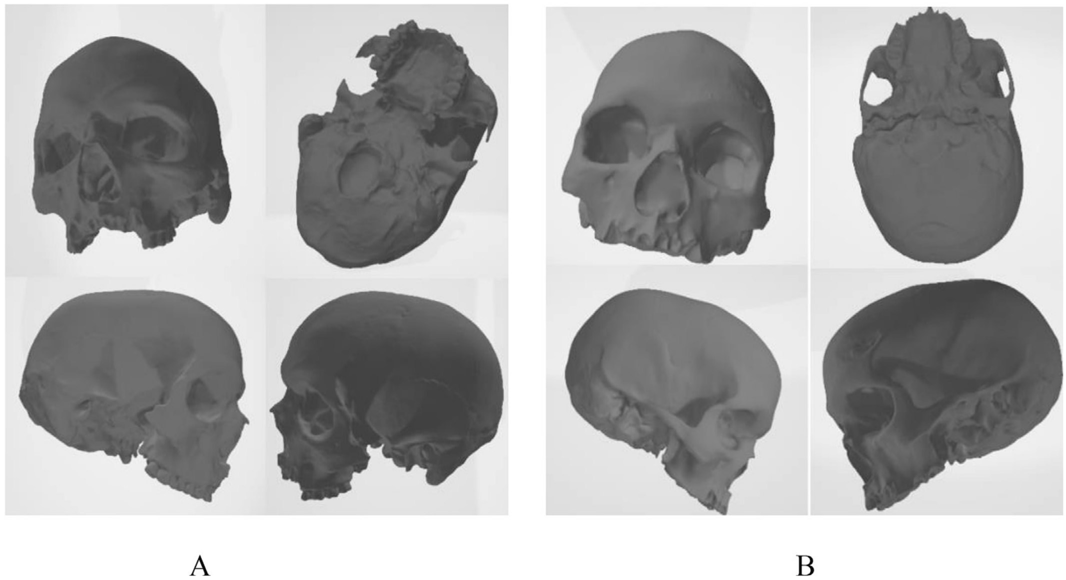

Fig. 2. A: Digitally scanned data of cranium (Test data). B: Digitally scanned data of cranium (Reference data).

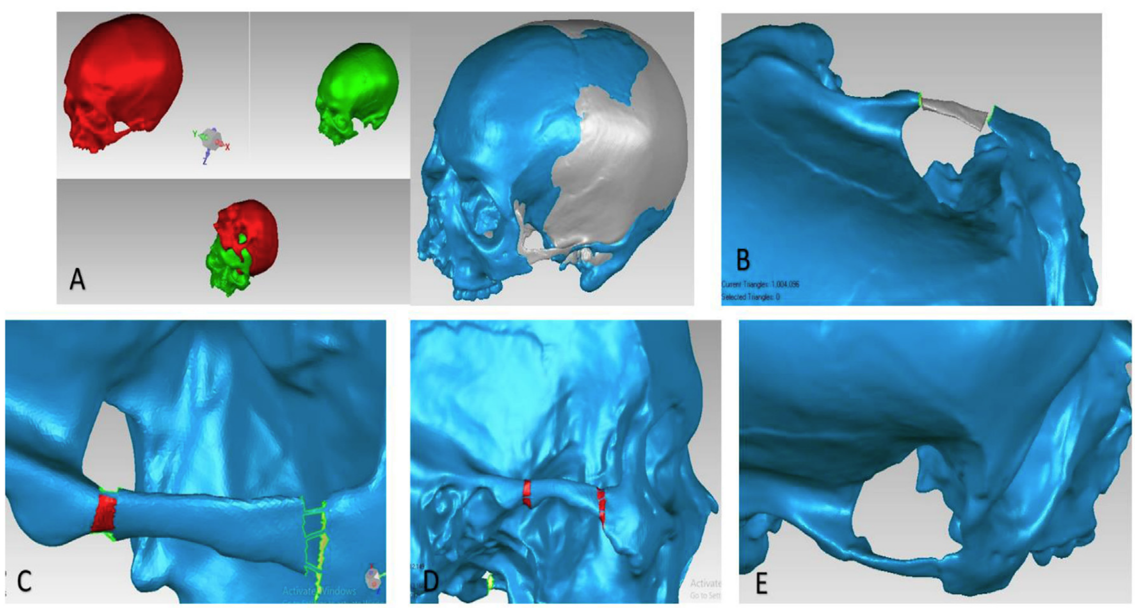

Fig. 3. Steps for reconstruction of missing zygomatic process (A) Manual Alignment and Global Registration (B) Replacing the missing element in the test data after extracting from reference data (C) & (D) Bridging the gaps using various methods. (E) Smoothening.

D. Replacement: After the alignments, the desired portion was selected and extracted from the fixed object (reference data) by using *'Lasso Tool'*, and was replaced in the missing space of floating object (test data).

E. Bridging: The bridge between the floating object (test cranium) and extracted portion (zygomatic process) was created by filling up the empty space using '*polygons*' and '*tangent*' methods.

F. Output: Following required use of wrap, polygons and noise reduction, the resultant object was smoothened and saved as '*. stl*' file.

2.4. 3D printing using fused deposition modelling

The resultant '*. stl*' file was used for printing the model of cranium using a Flashforge™ Guider 2 3D printer (Zhejiang Flashforge 3D Technology Inc., Zhejiang, China). The specifications [38]are build volume is 280 × 250 × 300 mm, printer material Polylactic acid (PLA), single nozzle, nozzle diameter 0.4 mm, precision ± 0.1–0.2 mm, forming technology is Fused Deposition Modelling (FDM), Flashprint printing software, thickness is 0.05–0.4 mm, speed 10–200 mm/S, 68% larger build volume, heatable build plate, AC input 100V–240V–500W. The printed model is shown in Fig. 4.

Fig. 4. 3D printed reconstructed model.

2.5. Analyses

Due to the absence of reference data, the morphology and the position of the reconstructed zygomatic arch was compared with the scanned data of the intact human cranium and to that mentioned in literature [39]. A direct articulation was established between zygomatic process of maxilla and temporal bone after reconstruction of zygomatic arch. The results were confluent with that mentioned in literature [39].

3. Case 2: Reconstruction of fragmented skeletal remains

3.1. Fragmented skeletal remains acquisition

After obtaining approval from the Ethics Committee of the institution, a human mandible was obtained from the skeletal archives of Laboratory of Forensic Odontology of Gujarat Forensic Sciences University, Gujarat, India for scanning purpose. A negative replica was made by using room temperature vulcanized silicone (Modsil-15) which was then filled with dental stone (Gold stone) to create the physical model. Metric analysis of the replicated mandible was carried out using a sliding Vernier caliper which showed overall discrepancy of 0–1 mm from the original. The replicated mandible was then fragmented by applying uncontrolled forces (Fig. 5). The replicated mandible was fragmented into nine pieces.

3.2. Scanning process

The nine pieces were numbered and then scanned with the Faro® 8-Axis Design ScanArm 2.5C Laser Scanner using the new Faro Prizm™ full colour Laser Line Probe with 3D design and modelling software with accuracy of 0.04 μm. The specifications [40] are high speed 8-Axis scanning up to 600,000 points per second, volumetric accuracy up to 75 μm.

Fig. 5. Fragmented replicated mandible.

3.3. Noise reduction

The initial scan was obtained as point cloud data. A noise reduction or filter process was performed. Scans were output as '. *stl*' files (Fig. 6).

3.4. Digital 3D reconstruction

For digital reconstruction, Geomagic Studio 13® (Geomagic Inc., 3D systems, North Carolina, USA) software was used. The workflow for the reconstruction of the fragmented mandible (Fig. 7) is summarized as follows:

A. Mesh processing: The point cloud data was converted into mesh using *'mesh doctor'* tab.
***B. Define objects*:** The first piece of replicated fragmented mandible was defined as *'fixed object'* and the second piece was defined as *'floating object'* in the software.
***C. Manual alignment*:** Both pieces (*fixed object & floating object)* were aligned in '*XYZ co-ordinates*'; by using *'manual alignment'* tool from '*n-point alignment*' selection under '*alignment tab*'. Three points were selected at homologous locations on fractured site of each piece in three planes (X, Y and Z). Thus, aligning both the pieces in complementary position.
***D. Global registration*:** To ensure accurate overlap of both the pieces and appearance of smooth surface, fine-tuning of the alignment between the two objects was achieved by '*global registration*' under the *'alignment tab'*. The automatic matching process (Global Registration) was initiated whose algorithm relies on minimizing the distance (mean square error) between two pieces. The same process (Steps B, C & D) was carried out for the rest of the pieces to reconstruct the replicated mandible (Fig. 7).
E. Output: The resultant object was smoothened and saved as '. *stl*' file.

3.5. 3D printing using fused deposition modelling

The resultant '. *stl*' file was used to remodel the replicated mandible using a Flashforge™ Guider 2 3D printer (Zhejiang Flashforge 3D Technology Inc., Zhejiang, China). The model was

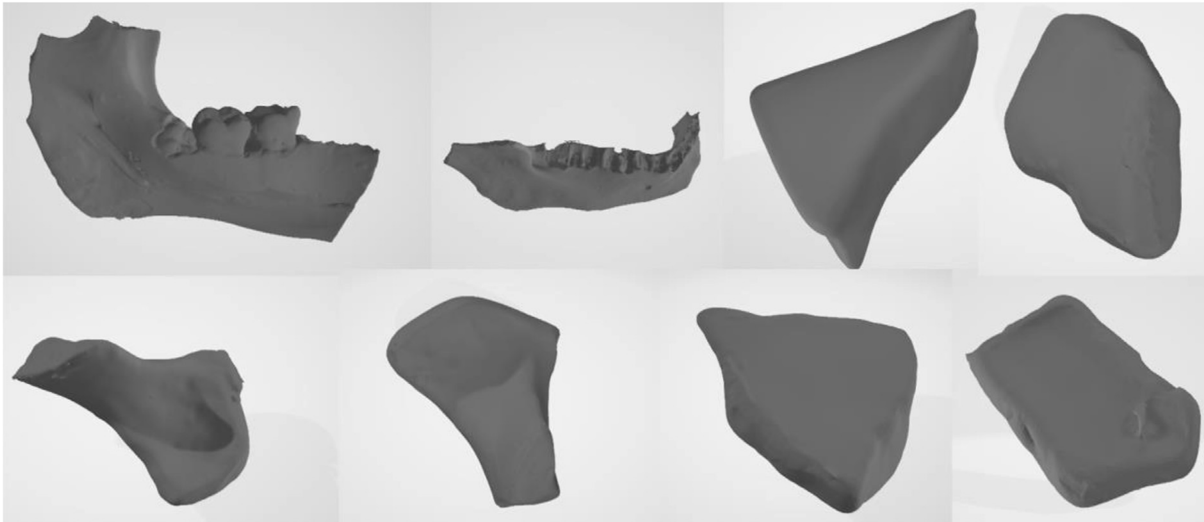

Fig. 6. Digitally scanned data of the fragments of replicated mandible.

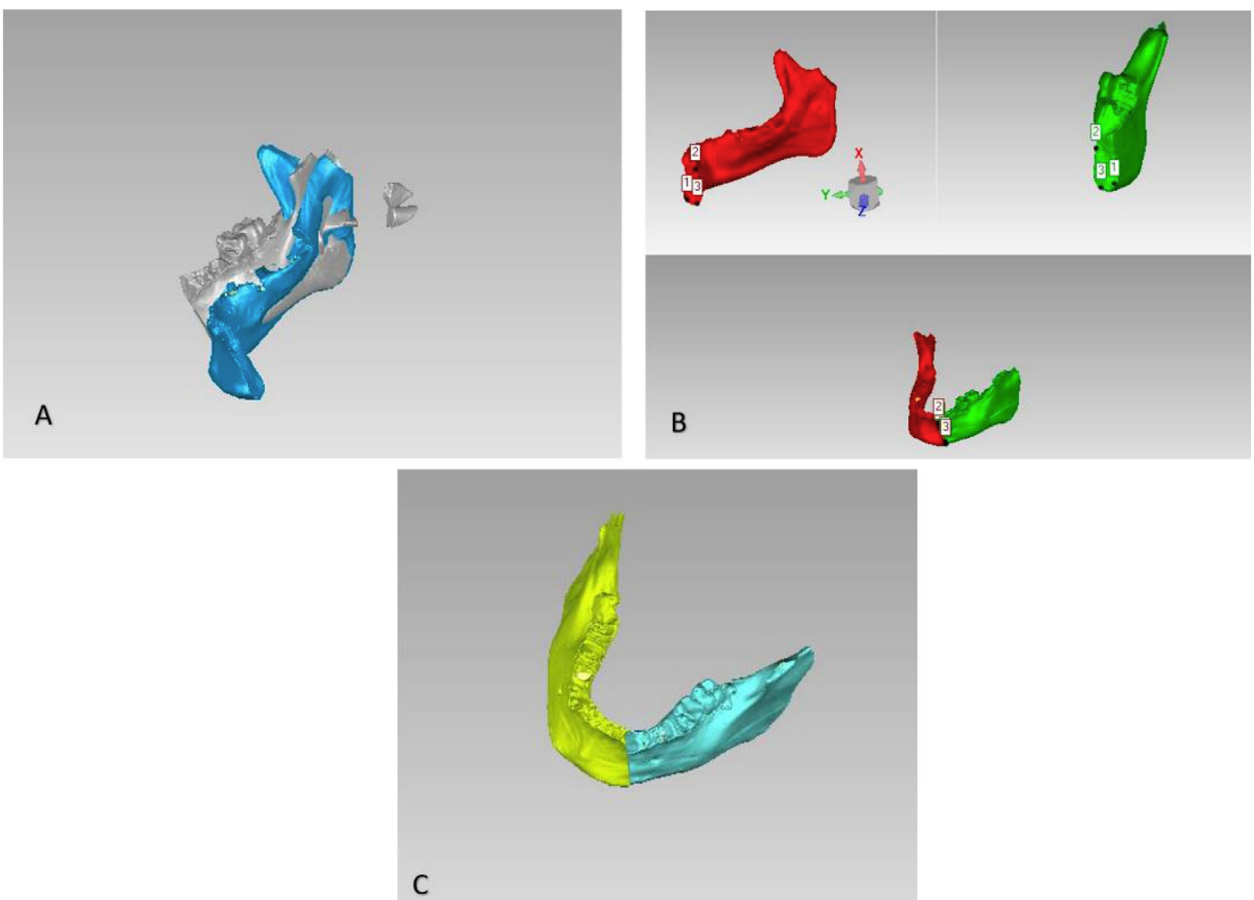

Fig. 7. Reconstruction procedure (A) Importing all the parts (B) Manual Alignment (C) Global Registration.

printed using Polylactic acid (PLA) by Fused Deposition Modelling process as shown in Fig. 8.

3.6. *Osteometric measurements*

Various linear measurements of the mandible were obtained from the reference/original mandible, replicated mandible and 3D printed model. All measurements were taken three times and the average used. These measurements were used to evaluate the accuracy of the reconstructed models (Table 1). On the basis of the measurements, the discrepancy obtained between the natural and the FDM printed mandible were 0.27 mm for chin height, 0.18 mm

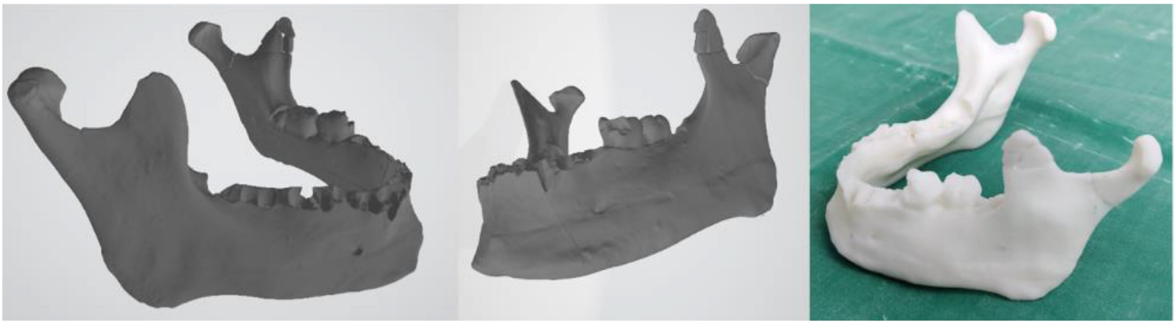

Fig. 8. Conversion in '.stl' file after aligning all the parts (left) and printing using FDM technology (right).

Table 1
Linear measurements of the reference mandible and 3D printed replica to evaluate.

Parameters	Original mandible (in mm)	Replicated mandible – before smashing (in mm)	3D printed mandible (FDM) (in mm)
Chin Height	23.42	23.40	23.69
Height of Mandibular body at mental foramen	25.1	25	24.92
Bigonial width	91	91	91
Bicondylar width	86.95	86.90	86.89
Min. Ramus breath	28.90	28.89	28.92
Max. Ramus height	63.15	63	62.01
Mandibular Length	81.16	80.89	80.37
Mandibular Body breath at Mental Foramen	8.86	8.80	8.65
Mandibular Body breath at M2/M3 junction	18.03	18	17.42
Dental Arcade width at third molar	49.44	49	48.90

for height of mandibular body at mental foramen, 0.00 mm for bigonial width, 0.06 mm for bicondylar width, 0.02 mm for min. ramus breath, 1.14 mm max. ramus height, 0.79 mm for mandibular length, 0.21 mm for mandibular body breath at mental foramen, 0.61 mm for mandibular body breath at M2/M3 junction, 0.44 mm for dental arcade width at third molar.

3.7. 3D digital qualitative congruency analysis

A qualitative congruency analysis between scanned data of the reference mandible and reconstructed model is show in (Fig. 9) (see Table 2). The maximum error range was set between −2.00 mm and +2.00 mm. The areas of positive error are represented by yellow, orange and red regions, and the areas of negative error are represented by blue regions. Areas where the error is within ±2.00 mm are represented by green region. The mean ± standard deviation (SD) of the root mean square (RMS) values is 1.5501 ± 2.00 mm, implying the overall level of variance of morphological error is 1.5501 ± 2.00 mm. The average value and variance are represented as 2.4028 mm and 1.0971 mm respectively. These results imply that the reconstructed 3D model can be used for various morphometric analysis.

4. Discussion

Three-dimensional surface scanning (3DSS) has the ability to collect data from various directions/angles without physically handling [41]. Previous work has demonstrated that this approach to recording and analysing human remains is superior to 2D and photogrammetric methods [9,42–47].

In cases where one of the paired bones is missing, reflecting the intact side and mirroring it on the other half has been documented [1]. Two methods [48] for reconstruction of the missing data on the skull have been previously proposed: one of them is statistical reconstruction that requires a reference population and takes into account variance and covariance within it which yields good results [48]. The other method, geometric reconstruction, uses properties of the thin-plate spline function and the data about one reference and one target [48,49]. It has more dependence on the properties of the reference shape [48,49].

In the present experimental approach, a bilaterally missing zygomatic arch was reconstructed digitally using the scanned data of a reference cranium with similar demographic data. For reconstruction of the zygomatic process the two crania were superimposed, with 34 of a maximum 100 iterations the average deviation was 0.986 mm with standard deviation of 0.794 mm which ensured the maximum positional accuracy which may further add on to this digital approach. After reconstruction and printing as described above, the cranium can be used for facial reconstruction and further analysis. Further, the remodelled fragment can also be given to search and recovery teams for retrieval of the missing element from the site of incidence. The major limitation inherent in the present study was the absence of reference data for appropriate validation, the results were based on literature and fundamental anatomical knowledge. While the reconstruction was carried out as objectively as possible, any reconstruction, physical or virtual, requires assumptions and a certain degree of subjectivity and user input [46].

Completeness of the fragmented remains is essential for establishing identification. The literature shows the use of geometric morphometric method [4] for reconstruction of paleoanthropological, anthropological remains where the fragments are reconstructed digitally [50]. The mandible reconstructed in the present paper relied on the manual algorithm which showed the overall morphological error of 1.5501 ± 2.00 mm. A lesser error rate can be predicted in case where original remains are reconstructed. The overall morphological error being less, this printed mandible can be used metric and non-metric analysis. The reconstructed mandible can be articulated with the cranium and may further aid with the identification process.

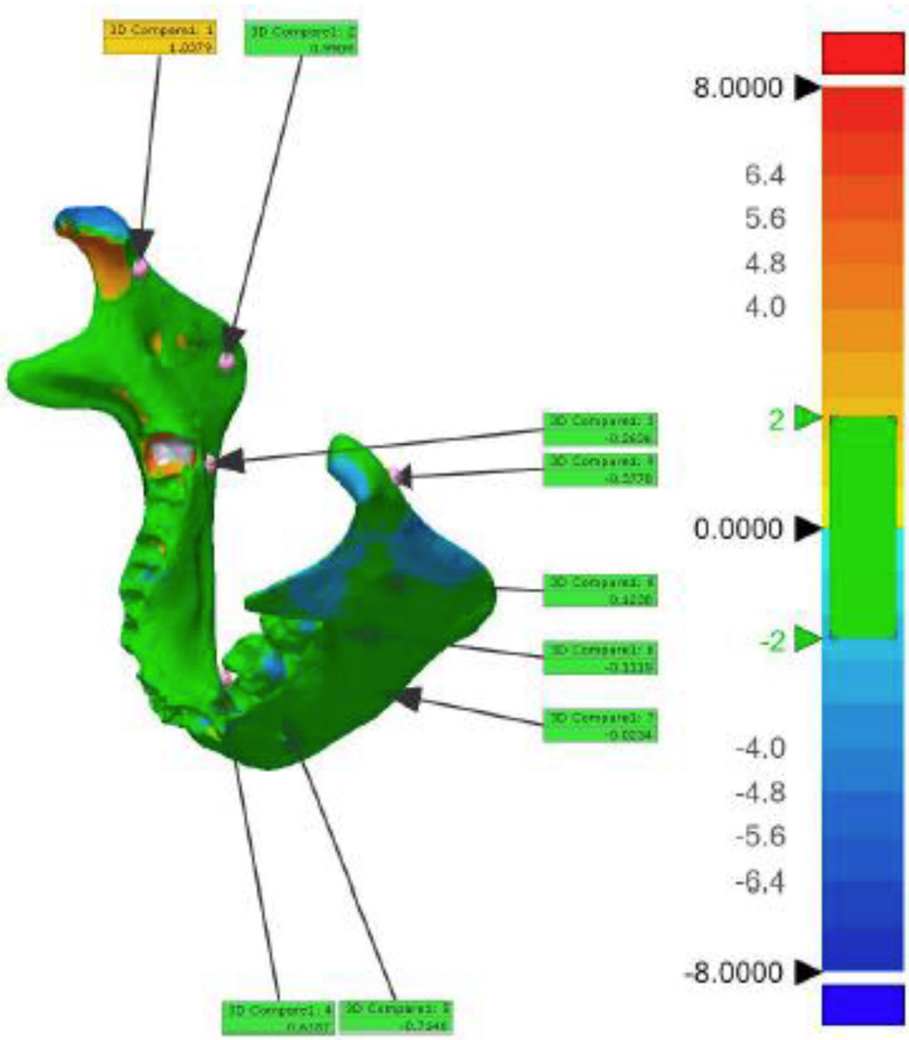

Fig. 9. Qualitative congruency analysis performed on scanned data of a reference mandible and a reconstructed mandible.

Table 2
Quantitative congruency analysis for case 2.

Compare	Gap distance	Reference mandible data			Reconstructed mandible data		
		X	Y	Z	X	Y	Z
point 1	1.0379	−202.0000	−202.0000	−202.0000	−202.0000	−202.0000	−202.0000
point 2	0.9909	−214.0000	−214.0000	−214.0000	−214.0000	−214.0000	−214.0000
point 3	−0.2636	−833.4028	−833.4028	−833.4028	−833.4028	−833.4028	−833.4028
point 4	0.6187	−201.0049	−201.0049	−201.0049	−201.0049	−201.0049	−201.0049
point 5	−0.7146	−213.7678	−213.7678	−213.7678	−213.7678	−213.7678	−213.7678
point 6	−0.1119	−833.5847	−833.5847	−833.5847	−833.5847	−833.5847	−833.5847
point 7	−0.0234	−196.1871	−196.1871	−196.1871	−196.1871	−196.1871	−196.1871
point 8	0.1238	−243.6278	−243.6278	−243.6278	−243.6278	−243.6278	−243.6278
point 9	−0.3778	−852.3379	−852.3379	−852.3379	−852.3379	−852.3379	−852.3379

Error in the metric analysis might derive from multiple sources i.e. scanning parameters, surface reconstruction parameters, scanner reconstruction algorithms, points selection, ruler positioning, and printing resolution [51,52]. Stull [53] state that an error range of ±2.0 mm is acceptable for anthropological assessments, while Langley [54] state that acceptable technical error of measurement (TEM) values are <1.5% for intra-observer error and <2.0% for inter-observer error. Furthermore, these differences have been identified as “clinically negligible” [55].

Carew [12] tested six printers with different process of printing and emphasized the SLA (Stereolithography) with laser curing printer type was the most metrically accurate. Special consideration shall also be required while 3D printing a cranium due to its size and the dense endocranial void as well [12]. FDM printers will be useful in this regards as it fills this void with a support scaffold [12]. These support scaffolds are not used in SLA may end up rough surface to leave [12]. We used FDM printers with gentle handling considering multiple sources of errors, achieved acceptable results.

5. Conclusion

Our work shows that human skeletal remains can be reconstructed accurately through (laser) surface scanning and subsequent 3D printing (using the Fused Deposition Modelling process), using two different methods – although solid anatomical knowledge and digital skills are required. India has a rapidly developing and maturing forensic sector and is confidently embracing digital tools such as these to support this work. Digital reconstruction offers a humanitarian approach to forensic investigation as there is minimal to no physical contact with the evidence, ensuring avoidance of damage to the osseous remains and the transfer of potential biohazards – particularly pertinent during the COVID-19 pandemic. Using this technology, the 3D reconstructed and printed model can be used for presentation in court. 3D printing in forensic anthropology and medicine is an emerging multidisciplinary topic, with major challenges that need to be addressed through empirical research. Further studies are needed in this field with other missing and fragmented cranial bones with a larger sample size, using different modalities of 3D scanning and 3D printing with other printing materials.

Ethics approval

The project was approved from the Institutional Ethics Committee; Gujarat Forensic Science University vide project no. GFSU/IFS/Ethics-FO/07-01/2019.

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Declaration of competing interest

No potential conflict of interest was reported by the authors.

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